Press Assoc.

White smoke cloud rises from atomic bomb hit on Hiroshima.

ATOMIC ENERGY

IN WAR AND PEACE

BY

GESSNER G. HAWLEY

Chief Technical Editor, Reinhold Publishing Corp.

Author of "Seeing The Invisible"

and

SIGMUND W. LEIFSON

Head, Department of Physics, University of Nevada

REINHOLD PUBLISHING CORPORATION
NEW YORK
1945

First printing November 1945
Second printing December 1945

Printed in the United States of America
by Ar-Kay Printing Co., New York

Lovingly dedicated

to

A. B. H.

Preface

ALTHOUGH hastily written and therefore justifiably to be considered a "quickie", this book is based on facts drawn from thoroughly reliable sources. The portion dealing with the details of the atomic bomb project follows closely the report prepared for the War Department by Professor H. D. Smyth of Princeton, and some of the preliminary background material is digested from certain fundamental articles in *Science* and *Time*. Bazzoni's "Energy and Matter" and Darrow's "Renaissance of Physics" have also been helpful sources of general information. Many details relating to the bomb project, which are contained in Professor Smyth's report, have been either subordinated or omitted, in an effort to give the reader the essential facts in a logically coordinated manner. If information that is interesting and pertinent is not given, it is because reasons of security required that it be withheld from the report released to the public.

It is hoped that this attempt to survey the subject of radioactivity and nuclear fission, from which atomic energy is derived, will be of service to those who have an elementary acquaintance with physics and who wish to obtain a fairly well-rounded view of the most remark-

able scientific achievement in history, and the future possibilities of this new force in the economic life of the nation. The authors have endeavored to state carefully and clearly the facts relating to the manufacture of U-235 and plutonium, even at the risk of being dull. The subject is so intrinsically fascinating that the most pedestrian presentation would be of interest.

We wish to express our thanks to the Misses Catherine J. Loeffler, Jill M. Sternberg, and Nives Hoffmann of the staff of the Reinhold Publishing Corporation, for their work in assisting in the prompt production of this volume.

We may well begin and end this resumé with a salute to the ability, courage, and devotion of all who participated in the atomic energy project.

G. G. HAWLEY
S. W. LEIFSON

October 5, 1945

Table of Contents

Table of Contents

"I can't believe that!" *said Alice.*

"Can't you?" the White Queen said in a pitying tone. "Try again: draw a long breath and shut your eyes."

Alice laughed. "There's no use trying," she said, "one can't *believe impossible things."*

"I dare say you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

—Lewis Carroll, "Alice Through the Looking-Glass"

1. Pandora?

"By the rude bridge that arched the flood,
Their flag to April's breeze unfurl'd,
'Twas there th' embattled farmer stood
And fired the shot heard 'round the world."

IN THE FAMOUS concluding line, Emerson was speaking metaphorically; but 170 years after the skirmish at Concord that it commemorates, another shot was fired—this time in the wastes of the New Mexico desert—which was the grimmest sort of realism. Had the materials been used in larger quantity, it is entirely possible that it would literally have been audible on the opposite side of the globe! In generations to come, that earth-rocking detonation may be regarded as marking an epoch in history even more significant than the opening shots of the Revolution.

Nor did it differ in any fundamental way from its historic predecessor of 1775; for the destructiveness of the atomic bomb is due to pieces of matter moving through space, just like the ball of a minute-man's musket. The difference in effectiveness lies in the weight of the projectiles and their speed: in one case a half-ounce pellet of lead propelled by the energy in a few grams of exploding black powder; in the other, particles of atomic mass traveling at a wholly inconceivable speed, hurled off by the

terrific energy within the atom. Nature's primeval secret has at last been spied out by man's insatiable curiosity about the world he lives in.

At first we may be inclined to visualize this astounding feat in terms of mythology, for it is too cosmic in its implications to be easily grasped by normal modes of thought. Pandora releasing the demons from the box; Prometheus pilfering the fire of the gods and bringing it to earth; Frankenstein's monster full of innate capacity for good; perhaps the fifth and most terrible Horseman of the Apocalypse! But in exploring the world of atoms and trying to comprehend the almost incalculable energy locked within them, we soon feel no need of the supernatural, for fairy tales and dream visions dim into drabness by comparison with scientific reality.

2. *Havoc*

HEAT ENOUGH TO vaporize steel; energy enough to devastate an area four-fifths of a mile in diameter! This was a small percentage of the power of the first atomic bomb dropped on Japan; yet it was light compared with a block buster. Suppose this little packet of annihilation had landed on Manhattan in the vicinity of Fifth Avenue and 50th Street. It would have wholly or partially destroyed every building in the area bounded by 57th Street on the north, Lexington Avenue on the east, 42nd Street on the south, and Eighth Avenue on the west. Such buildings as the Radio City skyscrapers, Grand Central

Press Assoc., Inc.

Figure 1. *All that remained of the steel tower from which the test bomb was dropped in New Mexico; the rest of it disappeared into the air as vapor. Left, Dr. J. R. Oppenheimer; right, Major-General L. R. Groves.*

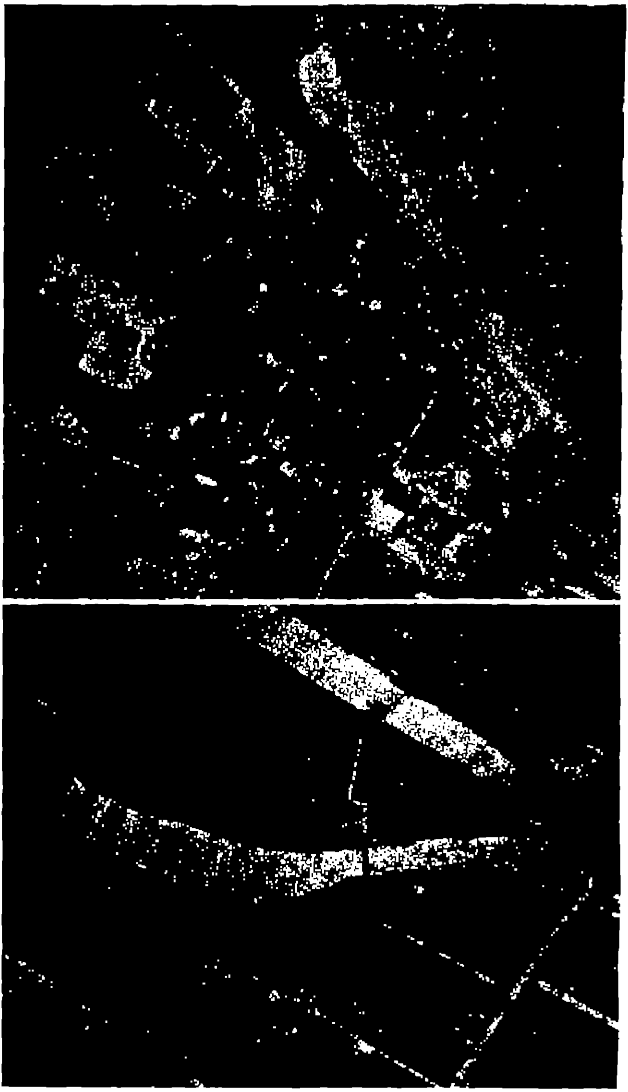
Terminal, the Waldorf-Astoria and the Times Square theater district would have been turned into heaps of rubble at a single blow! In the case of other cities it would have obliterated the entire Chicago Loop, knocked flat the Golden Triangle of Pittsburgh, and collapsed the heart of Boston's business area. Ford's vast River Rouge plant would have been blown to pieces by

a direct hit, as would the former German Krupp works in Essen. Yet as recently as 1940, in a review of the status and possibilities of atomic energy, the magazine *Science* stated that the uranium bomb "goes beyond fancy into the fantastic."*

A year later Vannevar Bush, former president of the Massachusetts Institute of Technology and Chairman of the National Defense Research Committee said he hoped that scientists "never would succeed in tapping atomic energy. It will be a hell of a thing for civilization."† A few days after Pearl Harbor, Dr. Bush became head of the Office of Scientific Research and Development which was established for the express purpose of laying plans for the atomic bomb project. He was not alone in his dismay at the possibilities; many other competent scientists shared his hope that this fearful secret would never be unearthed. Yet they knew that the Germans were on the verge of discovering it and were well aware of the military consequences if they succeeded. It is to the everlasting credit of Dr. Bush and his fellow-scientists who deprecated the release of atomic energy that they subordinated their personal opinions and devoted their unflagging efforts to the problem.

All this cataclysmic demolition caused by a few pounds of explosive charge? It sounds

**Science*, May 17, 1940, Vol. 91, p. 10 (suppl.).
†*Time*, May 26, 1941, p. 61.



Press Assoc., Inc.

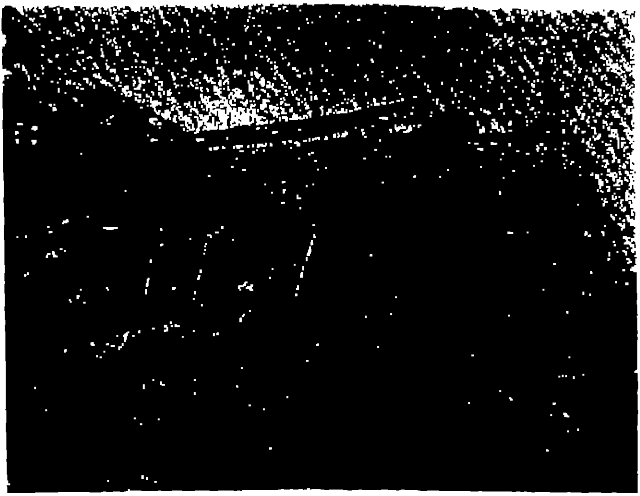
Figure 2. *What an atomic bomb did to Hiroshima. Above: city before attack; below: after explosion.*

incredible, especially when we realize that much of this weight was accounted for by the sheathing of the bomb, and that the energy itself emanated from only about five pounds of uranium. Its power, weight for weight, is about two thousand times that of TNT, and no less than five million times that of coal burned in the usual way. Is it any wonder that atomic energy has been visualized as an inexhaustible source of cheap power, which would replace all our gasoline, fuel oil, coal and water with the force of millions of Niagaras? A battleship could go around the world on the energy contained in a glass of water; electricity might be supplied to the entire country for two months on the power latent in a few handfuls of sawdust!

How is this terrific force released? Where does it originate? Can it be controlled? Could the world itself be rent asunder by perverted use of atomic power, or perhaps by accident? To answer such questions satisfactorily it will be well to start at the beginning of the story and review the fundamental knowledge necessary to understand the answers when we get them.

3. *What Is an Atom?*

If we are going to talk about splitting and disintegrating atoms, it is essential to have a correct idea of what an atom is. As it will be a great temptation to confuse atoms with molecules, a warning signal is herewith displayed at the very



Press Assoc., Inc.

Figure 3. *The huge Mitsubishi Steel Works were completely wrecked by the force of the mighty explosion a mile away.*

outset. An atom is the smallest possible particle *of any substance*. Up to fifty years ago atoms were thought to be the smallest absolute particles that can exist; but it has since been proved that they have a complicated internal structure composed of particles which are smaller still.

This may sound like double talk, but it most assuredly is not. By saying that an atom is the smallest particle of any substance, we mean that no substance could conceivably exist in any more subdivided form: an atom is the basic unit of a substance. That is not at all the same thing as being the smallest particle that can exist. Smaller particles *do* exist; but the component parts of

an atom of gold are not gold, or any other substance: they are really minute bundles of electricity and we shall have occasion to become intimately acquainted with them presently.

Ignoring for the moment the two new elements recently discovered, let us think of the physical universe as composed of 92 different kinds of atoms — 92 basic substances — which are called *elements*. These, either by themselves or in combination with one another, make up everything that we know as matter—from diamonds to soap and from sofa cushions to locomotives. If this is true, we should expect theoretically to be able to cut up, say a pillowcase, into finer and finer pieces, and find that way down in the submicroscopic range we would wind up with atoms. This is exactly true: we would have atoms of carbon, oxygen, and hydrogen.

4. The Greeks Had a Word For It

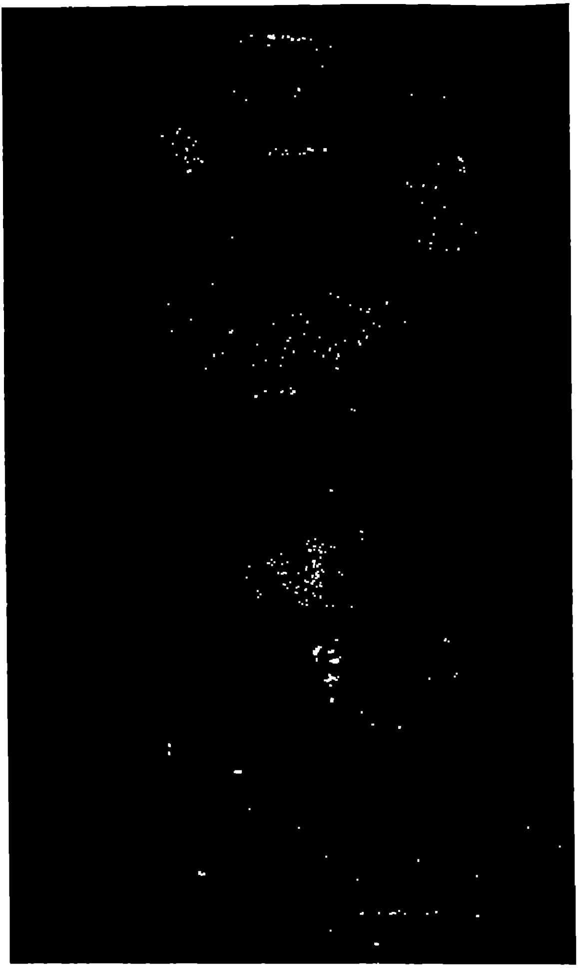
The concept of matter as existing in the form of separate particles is over two thousand years old. It is generally known that the word "atom" is Greek for "uncuttable" or "indivisible"—an idea which persisted until late in the nineteenth century. In the golden age of Greek civilization, philosophers occupied themselves with trying to guess what the world was made of, and some of them propounded quite ingenious theories. Aristotle, for instance, held that there were only

four kinds of matter—earth, air, fire and water. These he called elements; and in spite of the modern adoption of this word to designate one of the 92 kinds of atoms, it retains its old unscientific meaning to this day.

Most up-to-date of the Greek philosophers was Democritus, who was the original proponent of a strictly mechanistic explanation of the universe. He considered that matter is not at all as it appears to be—by which he showed himself a true scientist—but is composed of a never-ending rain of invisible, solid particles, which he christened atoms. How he came to hit on this notion is problematical; but it is a striking fact that, of all the great thinkers who lived between 400 B.C. and 1800, he alone visualized one of the basic realities of material structure.

No one seemed to pay much attention to his hypothesis, however. For centuries scholars were so enamored of Aristotle's ideas that they followed them with slavish devotion, to such an extent indeed that they refused to believe their own eyes when Galileo demonstrated the principle of acceleration of falling bodies in his famous Tower of Pisa experiment.

During the Middle Ages the alchemists—the practical scientists of their day—were less devoted to the search for truth than to discovering a cheap and easy way to turn common metals into gold. It would be interesting to know the origin of the idea that this could be done. The search went on in medieval laboratories for gen-



From Child, "Tools of the Chemist" (Reinhold)

Figure 4. *Alchemist's Laboratory. From exhibit in Deutsches Museum, Munich.*

erations, but the closest they ever came to it was a preparation of fine particles of gold in water. The specks of gold were so minute that they remained suspended in the water, giving it the appearance of liquid gold. Scientists now call such a suspension a colloidal solution. The alchemists and their hope of transmuting other substances into gold are mentioned here because *this feat was recently accomplished by atomic disintegration.*

5. The Atomic Theory

Early in the nineteenth century came one of the most remarkable scientific theories ever advanced, which was so accurate in its details that it has ever since been the cornerstone of chemistry. It was due to the constructive imagination and the scientific acumen of an Englishman—John Dalton. Democritus' idea of atoms was sheer guesswork; Dalton's was founded on mathematical certainty. Moreover, Dalton's theory went far beyond a mere statement that matter is made up of infinitesimally small particles; it predicted with uncanny accuracy the exact ratios in which the atoms would combine to form compounds, and stated that they are held together by forces which vary in strength with the kind of atom.

Dalton was a theorist rather than an experimenter; but his contemporaries, struck by the positiveness of his conclusions, proceeded to in-

vestigate them thoroughly. A tremendous flood of basic research was carried out by Berzelius, Liebig, and others, with the result that Dalton's atomic theory was definitely established as a fact. They found, for example, that atoms have specific combining ratios which are universally valid; and also that each element has a characteristic attractive force which binds it to others. This force they called *valence*, although its electrical nature was not determined for some time.

6. *Perpetual Motion*

Though the different kinds of atoms vary in size, none of them is large enough to be visible in the most powerful microscopes yet devised; but it is possible that the largest of them may some day be distinguished in the electron microscope. The smallest atom, hydrogen, is so tiny that it would take over two hundred million of them to equal an inch; the large ones are six or eight times as big.

Atoms are in perpetual motion, and their speed is tremendous. Depending on their mass and on whether or not they are accelerated by heat, they are incessantly tearing around at rates varying from 5,000 to 25,000 feet a second. Only at a temperature of 273 degrees below zero centigrade would their motion cease completely. This has been very closely approached experimentally, but never quite attained; if it were, the substance would completely disintegrate.

Even within a few degrees of the so-called absolute zero, steel would fall apart at the touch of a straw!

Naturally atoms come into rather violent contact with one another as they dance endlessly about; each atom indeed can travel only a microscopically tiny distance without bumping into another atom. Such atomic collisions occur billions of times a second for each atom—unimaginable as this fact may be. The result of the collision, of course, is an abrupt change of the direction of both the atoms concerned; thus the best practical way to visualize atomic motion is by comparing it to "the whirldance of the blinding storm", in which billions of snowflakes are zigzagging across the line of vision.

Though perpetual motion can never be attained with a machine because of friction losses, it is a reality in the world of atoms. If this were not so, the universe would have run down and stopped long ago. The reason why atoms never slow down when the temperature is kept constant is that they do not lose any energy when they collide with their neighbors. This is an astonishing fact, which is not true of objects of visible size, like golf balls. But before finishing this book we shall discover many other inconceivable things, so perhaps this is as good as any to begin with.

When a golf ball is dropped to the floor from a height of say three feet, it rebounds about two feet the first time, a little less the second time,

and so on, its rebound distances decreasing rapidly till it finally comes to rest: all the energy imparted by its fall has been taken up by the floor. The same would be true of a room full of golf balls colliding with one another and the walls; in a few moments all of them would be lying still on the floor because they would have given up their energy either one to another, to the walls, or to the floor. Such collisions as these are called *inelastic,* which means that they involve energy loss. The motions of all visible material bodies are inelastic to a greater or lesser extent. Atoms, however, behave differently, and their collisions are described by physicists as "perfectly elastic"; that is, when one atom strikes another it loses no energy whatsoever. Thus it will retain its speed unchanged indefinitely at any given temperature. Elasticity is merely the extent to which a substance recovers after deformation—not, as popularly considered, its susceptibility to being pulled out of shape. Glass, for instance is very highly elastic; rubber is considerably less so. Atoms are 100 per cent elastic, and are not worn out by fatigue after repeated collisions.

7. The Periodic System

EACH OF THE 92 elements has been weighed with the most minute exactness; the lightest one, hydrogen, has an atomic weight of 1.008, and the others range up to 238 for uranium, the

heaviest. In order to classify the elements, they are arranged in a table in the order of increasing atomic weights, and each one is assigned a number indicating its position in this table. Thus there are two characteristic numerical values associated with each element: first, its *atomic weight* and secondly its *atomic number*. For example, the atomic weight of oxygen is 16.00 (that is, it is about sixteen times as heavy as hydrogen) and its atomic number is 8, meaning that it is eighth in order of the elements in the table just referred to. Atomic weights are not given in any units, such as pounds or grams; they are *relative* values showing the weight ratio between an atom of one substance and that of another. *(see p. 16)*

This table is so important that it should be studied by all who wish to understand the principles underlying atomic energy. As it will be necessary to refer to it repeatedly in this book, it is here reproduced in full. It was first worked out about 1870 by the Russian scientist Mendeléef. He noted that when he listed the elements in the order of increasing atomic weights, there was a marked similarity between them at regular numerical intervals. For example lithium, third in order of atomic weight, has many of the same properties as sodium, which is eleventh in order; and sodium in turn behaves like potassium, which is in nineteenth position. In short, there is a recurring or "periodic" similarity between the elements at intervals of 8:8:18:18:32.

Atomic Number at left of element

THE PERIODIC TABLE

Atomic Weight below

	A I	B	A II	B	A III	B	A IV	B	A V	B	A VI	B	A VII	B	A VIII			B
1	1 H 1.008																	2 He 4.00
2	3 Li 6.94		4 Be 9.02		5 B 10.82		6 C 12.00			7 N 14.01		8 O 16.00		9 F 19.00				10 Ne 20.18
3	11 Na 23.00		12 Mg 24.32		13 Al 26.97		14 Si 28.06			15 P 31.02		16 S 32.06		17 Cl 35.46				18 A 39.94
4	19 K 39.10		20 Ca 40.08		21 Sc 45.10		22 Ti 47.90		23 V 50.95		24 Cr 52.01		25 Mn 54.93		26 Fe 55.84	27 Co 58.94	28 Ni 58.69	
		29 Cu 63.57		30 Zn 65.38		31 Ga 69.72		32 Ge 72.60		33 As 74.91		34 Se 79.2		35 Br 79.92				36 Kr 82.9
5	37 Rb 85.44		38 Sr 87.63		39 Y 88.92		40 Zr 91.22		41 Cb 93.3		42 Mo 96.0		43 Ma	.	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	.
	.	47 Ag 107.88		48 Cd 112.41		49 In 114.8		50 Sn 118.70		51 Sb 121.76		52 Te 127.5		53 I 126.92				54 Xe 130.2
6	55 Cs 132.91		56 Ba 137.36		RARE EARTHS		72 Hf 178.6		73 Ta 181.4		74 W 184.0		75 Re 186.31		76 Os 190.8	77 Ir 193.1	78 Pt 195.23	
		79 Au 197.2		80 Hg 200.61		81 Tl 204.39		82 Pb 207.22		83 Bi 209.00		84 Po 210.		85				86 Rn 222.
7	87		88 Ra 225.97		89 Ac 226.+		90 Th 232.12		91 Pa 230.		92 U 238.14							

Interval 8

Interval 8

Interval 18

Interval 18

Interval 32

RARE EARTHS							
57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 Il 146.	62 Sm 150.43	63 Eu 152.0	64 Gd 157.3
65 Tb 159.2	66 Dy 162.46	67 Ho 163.5	68 Er 167.64	69 Tm 169.4	70 Yb 173.5	71 Lu 175.0	

Neptunium and Plutonium, the two newly discovered elements, have not yet been assigned places in the Periodic Table.

Investigating this further, Mendeléef worked out a grouping method based on atomic weights, which has since been known as the Periodic System. Its importance is that it classifies elements having similar chemical properties into eight major groups, and shows at a glance the position and relationship of each element to every other element.

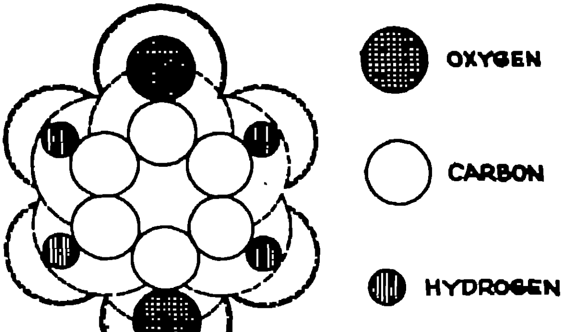
When Mendeléef first presented this system there were several missing elements, represented by blank spaces. So accurate was his work that he was able to predict that these elements would eventually be found. Sure enough, they were, and their weights corresponded almost identically to what Mendeléef had expected.

8. *What Is a Molecule?*

THE WORD "MOLECULE" means literally "a little structure." A molecule is a combination or union of two or more atoms; if the atoms are of different kinds, the combination is called a *compound,* and the molecule is the smallest possible unit of that compound. It frequently happens that two or more atoms of the *same* element unite to form a molecule; for example, the life-supporting gas, oxygen, occurs in molecular form in which two atoms of oxygen are combined, and has a *molecular* weight of 32, or 2×16. Such a molecule is not a compound, however, as it can be divided to give two separate *atoms* of oxygen.

When the combining atoms are different, the

resulting molecule cannot be subdivided without destroying the compound. As everyone knows, a molecule of water is made up of two atoms of hydrogen and one of oxygen; therefore the molecule designated H_2O is the smallest quantity of *water* that can exist. If we attempt to divide it, we cease to have water—all we get are the two gases, hydrogen and oxygen. It is interesting to note in passing that the physical form of an element has no bearing on the form of



From Hawley, "Seeing the Invisible" (Knopf)

Figure 5. *The structure of a typical molecule, and comparison of its size with that of its atoms.*

compound of which it is a part. Here is a case where two *gases* combine to form a *liquid*. Such phenomena are commonplace in chemistry.

In the accompanying diagram is shown the structure of a typical molecule, or compound; beside it are the individual atoms of which it is composed. A compound such as this is called a *carbohydrate;* if there were no oxygen in it it would be a *hydrocarbon*.

9. Chemical Changes

Under various influences atoms combine in exact proportions to form compounds, just as Dalton had said they would. They can also be made to separate, thus breaking up the compound. These processes of combining and coming apart are called *chemical changes,* or reactions. They are always accompanied by a gain or loss of heat caused by formation or disruption of the valence forces in the molecules which take part in the reaction. As previously mentioned, these are the forces that hold the atoms together in the molecule. Some compounds react with each other at room temperature; others require application of heat to start the reaction. The latter fact accounts for the presence of Bunsen gas burners in chemical laboratories.

Chemical changes are constantly going on both around and within us; everywhere compounds are breaking down and new ones being formed. The human body is a great chemical plant in which molecules of fat, starch, sugar and protein are disrupted by combining with the oxygen we breathe, to form the heat and energy that keep us going. The souring of milk, the rusting of iron, the explosion of nitroglycerin, and the decay of vegetable matter are a few common instances of atoms breaking loose from their original groupings in the molecule and rearranging themselves in new forms.

As just remarked, these rearrangements involve gain or loss of *heat,* which is a form of *energy*. As energy is the main theme of this discussion, we shall define it forthwith as the *capacity of a body or mass to exert force,* or in the language of physics, to do work.

10. How Big Are Molecules?

LIKE ATOMS, MOLECULES have a definite weight, which is merely the sum of the weights of the atoms composing them. In the case of water, since the atomic weight of oxygen is 16.00 and that of hydrogen 1.00, the molecule H_2O has a weight of $(1 \times 2) + 16$, or 18. For more complicated compounds like sugar ($C_6H_{12}O_6$) the molecular weight would be:

$$(6 \times 12) + (12 \times 1) + (6 \times 16) = 180$$

(The atomic weight of carbon is 12).

Molecules have a vastly greater range of sizes and weights than atoms. Some of the larger ones, which are characteristic of plastics and proteins, are tremendous; they would compare in size with a molecule of water as a dirigible would with a golf ball. These big fellows are sometimes called macromolecules, and their molecular weight runs up into the millions. Molecules of ordinary size are invisible in any microscope; but the giant ones can be seen in the electron microscope.

11. How Many Compounds Are There?

How many kinds of molecules make up this crazy world of ours? All you have to do to answer that question is figure out the number of possible combinations permitted by 92 elements! Over 500,000 compounds containing the element carbon have been identified to date; these are known as *organic* compounds. It is conservative to say that about 700,000 different sorts of molecules are known, and that many more exist.

Much could be written about molecules and their fascinating behavior; but as they have only an indirect bearing on atomic energy, we shall not go further afield. It will be necessary, however, to keep in mind the essential difference between them and atoms; for it must be clearly understood that molecules, or compounds, *constitute our normal supply of energy,* and that the power of the atomic bomb is derived from an *abnormal* source—which is the atom.

12. Keeping Warm

Since his first appearance on earth man has been extracting energy from matter. The first thought of the caveman was to eat, and the second was to keep warm. As he needed fire for both purposes, he promptly discovered it. Presumably wood or animal oil was used for fuel for many centuries; then came peat, low-grade coals, and anthracite, and in the modern era petroleum, gas, and electricity. When the first

Rough Stone Ager got a spark by rubbing two sticks together (a feat which would embarrass most people of considerably higher I. Q.), he had no idea that he had hit upon one of the most important chemical reactions on earth—he just wanted to roast his wild boar. Nor did he know that the wood he used was composed of molecules of cellulose, which in turn were built up of carbon, oxygen, and hydrogen atoms. He probably did not even realize that by burning wood he was releasing some useful force stored within it; and he didn't care.

13. *The Energy in a Molecule*

Any compound which contains carbon and hydrogen will burn and give off energy in the form of heat and light. This reaction, or combustion, is caused by union of the oxygen atoms of the air with the carbon and hydrogen atoms of the fuel. When this union takes place, the original compounds of which the fuel is composed are destroyed and are replaced by new ones. The heat, or *thermal* energy, is evolved due to rupture of the forces binding the fuel compounds together. The light, or *radiant* energy, has a somewhat different cause which will be mentioned later.

We recall that Dalton had postulated the existence of attractive forces, which hold the atoms together in a molecule, and that they were designated as *valence*. When oxygen reacts with

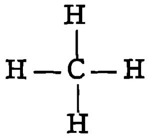
carbon, as it does when a fuel is burned, these valence forces are disrupted, and the energy thus released is the source of the heat. Of course it is necessary to initiate the reaction by applying heat; but once started, it perpetuates itself as long as the supply of fuel holds out.

A piece of wood is comprised chiefly of complicated molecules of cellulose; and the valence forces in such a molecule are quite numerous. They may be visualized as bonds which tie the atoms securely together. The carbon atom has four of these bonds, the oxygen atom two, and the hydrogen atom one. It has been calculated that the rupture of the four bonds of the carbon atom releases energy equivalent to four electron volts. Compare this with the 200 million electron volts produced by splitting a uranium atom and you have a fair idea of the difference between combustion energy and atomic energy.* It should be emphasized, however, that though this seems like a very large energy value, it is small in terms of our ordinary conceptions. It would hardly be enough to start a watch running; yet in comparison with the size of an atom it is truly titanic.

*An electron volt is a very small unit equivalent to the energy of an electron activated by one volt. The number of electrons involved in the rupture of chemical bonds is so vast that an impressive amount of total energy is built up.

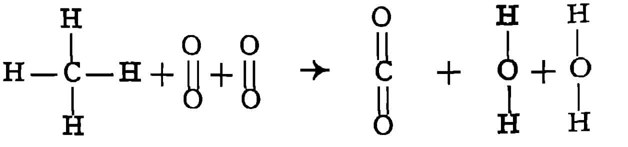
14. *Why Fuels Burn*

Let us take a very simple instance of combustion and examine it as the chemist does. A good fuel to use for this purpose is the hydrocarbon gas called methane, which is found in natural gas, in mine shafts, and anywhere else where there is decaying vegetable or carbonaceous material. This molecule is composed of one atom of carbon, to which four atoms of hydrogen are securely attached by valence bonds, thus:



or CH_4

Suppose now that we burn this molecule, that is, add oxygen to it. Here is what happens, viewed from the structural standpoint; the vertical lines represent the valence forces, or bonds:



methane (1 molecule) *oxygen (2 molecules)* *carbon dioxide (1 molecule)* *water (2 molecules)*

In this rearrangement the four bonds tying the hydrogen atoms to the carbon atoms in the methane molecule have been broken and two atoms of oxygen have replaced the hydrogen. In the newly formed compound, carbon dioxide, it is evident that the carbon atom still has the same number of bonds that it started out with, except that now they are attached to atoms of

oxygen. The hydrogen atoms, meanwhile, have united with other oxygen atoms to form water. Thus two products of any organic combustion reaction are always carbon dioxide and water. Since it is the addition of oxygen to carbon that causes combustion, the process is generally referred to chemically as *oxidation.*

15. Chemical Balance

It is usually unnecessary to write reactions in such a detailed way; but for the purpose of this discussion it is desirable, because our object is to discover the true source of the energy in ordinary substances, so that the difference between energy from *molecular rearrangement* and energy from *atomic disintegration* will be clearly understood. A simpler way of indicating the reaction just described is:

$$\underset{\textit{methane}}{CH_4} + \underset{\textit{oxygen}}{2O_2} \rightarrow \underset{\textit{carbon dioxide}}{CO_2} + \underset{\textit{water}}{2H_2O}$$

Translated into words, this equation states that one molecule of methane plus two molecules (or four atoms) of oxygen produce one molecule of carbon dioxide and two molecules of water. It is a cardinal principle of chemistry that the total number of atoms on one side of the equation must be equal to the total number on the other side; as chemists say, the equation must *balance.* Adding them, we find that this is the case: there is one carbon atom on the left of the arrow and one on the right. Similarly, there

are four atoms each of oxygen and hydrogen. They are, however, in different molecular combinations. This balance can be checked by adding the molecular weights of the substances on both sides, thus:

[12+4]	+	[2(16×2)]	=	[12+(16×2)]	+	2[2+16]
methane		*oxygen*		*carbon dioxide*		*water*
16	+	64	=	44	+	36
		80	=	80		

16. Free Energy

BUT WAIT A MOMENT! Perhaps we are going too fast! Have we really accounted for all the facts of combustion in writing this reaction? True, all the atoms of methane and oxygen have been properly placed, and we find that they form equivalent weights of carbon dioxide and water. But the essential point of the reaction in the first place was to get some heat out of it; the equations written so far have left our caveman shivering and in anguish with nothing but chemical symbols to keep him warm! What has happened to the *energy* resulting from the changes in molecular structure? Should it not be represented in the reaction?

Yes, of course it should. So to give a true picture of what happens in a combustion or oxidation reaction we must rewrite it as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \Delta$$

methane *oxygen* *carbon dioxide* *water* *energy*

The energy liberated is conventionally indicated by the Greek letter delta (Δ), which

stands for energy increment. But adding this component to the equation creates a new problem, for does it not destroy the balance which was so precisely arranged before? It surely looks as if this energy factor makes the equation lopsided—as if we were getting more out of the original substances than we should. The heat and light do come out; that is indisputable. On the other hand, the number of atoms and their molecular weights balance to a nicety. Yet something impels us to ask which is the correct state of balance—with or without the Δ increment? The "something" that prompts this query is probably the most fundamental principle in all nature.

17. *A Closed Corporation*

Although it is perfectly possible to get something for nothing in the economic world—an accomplishment that sometimes becomes a ruling passion—nature is not so lenient. She simply refuses to be cheated, or to give up anything more than she receives. Her rule is that if there are 100 atoms involved in a reaction to start with, every one of them must be accounted for in the products of the reaction. If a certain amount of energy is put into a machine, precisely that amount will be delivered—no more and no less. This law is so basic, so universally true, that it is idle to speculate about there being any physical phenomena that do not obey it. There

are none. It is known as the law of *conservation of energy.*

The principle may be stated in its simplest form about like this: the total amount of energy in the universe is *constant; energy can never be created or destroyed,* although its form can be changed. This means that never from the beginning of time has a single unit of energy been added to the total energy of the universe, nor has a single unit been removed. All the transformations—the infinite number of chemical changes that are constantly taking place—are merely turning energy from one *form* into another without affecting the total in the slightest.

As we reflect upon the implications of this principle we begin to think of matter less and less in terms of visible objects like butter and shoes and baseballs, or even of molecules and atoms. We catch a glimpse of a fact to which more explanation will be devoted in a later section—namely, that energy, which we see manifested in heat, light, and power, is the most fundamental reality of the physical world. Everything comes from it and turns back into it. Nature is a closed corporation.

18. Where Do Fuels Get Their Heat?

NOW TO GET back to the equation, we realize a little more clearly what it was that made us hesitate to accept it as finally written with the free

energy included. For convenience, here it is again:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \Delta$$

The law of conservation of energy holds that there can be no heat and light extracted from methane and oxygen unless they were originally present in one or both of them. Knowing that this law admits no exceptions, and knowing also, as a practical truth, that fuels do contain some form of thermal and radiant energy, we ask ourselves how the energy got there and how it manages to stay there for thousands of years without dissipating itself. Frozen energy! That is basically what a stick of wood, a barrel of oil and a container of natural gas are.

Looking at the compound CH_4 we see it is formed by the union of one carbon atom and four hydrogen atoms. From what was said before we know that a certain amount of energy is necessary to get these atoms to unite to form a compound. Why did they join in the first place? And where did the energy come from?

It is a little easier to understand this problem if we use a piece of wood as an illustration. What force acted upon the original atoms to make them combine to form wood originally? What force makes any vegetation grow? The answer is obvious: *sunlight!*

19. How Fuels Were Made

THE SUN IS the ultimate source of all the energy stored in fuels. When well up toward the zenith,

it furnishes about 1.5 horsepower to every square yard of the earth's surface on which it shines. Vegetation is equipped with a marvelous and in some ways still secret method of utilizing this unending inundation of power. The green coloring matter of leaves, called chlorophyll, is able to use it in such a way that the tree or plant can form carbohydrates from the carbon dioxide in the air and the water in the ground. This process is known as photosynthesis, and the chemical reaction is:

$$\underset{\textit{carbon dioxide}}{6CO_2} + \underset{\textit{water}}{6H_2O} + \underset{\textit{energy}}{\Delta} \rightarrow \underset{\textit{sugar}}{C_6H_{12}O_6} + \underset{\textit{oxygen}}{6O_2}$$

The essential product is of course the sugar molecule, for it is the base from which more complicated carbohydrates like cellulose are built up—and wood is mostly cellulose, ($C_6H_{10}O_5$). Note that this time the Δ is on the input side of the equation.

Thus the energy bestowed upon the plant by sunlight is used to make molecules of wood. Viewed in this way, wood and its carbonized form, coal, are merely vast storage depots of solar energy, which is released when the carbon atoms are oxidized. The law of conservation of energy is fulfilled; for this energy was originally derived from the sun when the molecules were formed. Some of it is given off as *light,* or radiant energy, in the same units as originally taken up from the sun.

20. Petroleum

Once more referring to the equation using methane as a source of heat, we now see that the energy built into its molecule was also originally due to sunlight, for methane is formed from decomposing vegetable and other organic matter. It is often found in swamps and peat bogs, and is frequently known as marsh gas; in coal mines it constitutes the so-called "fire-damp".

Petroleum, from which we derive so many useful forms of fuel, is thought to have been formed from plant and animal life buried in the earth in geologic eras millions of years ago. There are several theories as to how this occurred which are of no importance here. It is a fact, however, that petroleum is not a single chemical compound, but an extremely complicated mixture of hundreds of different hydrocarbon molecules. All these combinations of carbon and hydrogen atoms were formed, like methane, by solar energy; and the heat and power we obtain by burning or oxidizing them is merely a release of the force which had its origin in the sun, 93 million miles away, and about as many years ago!

21. Frozen Energy

Why does the heat latent in the molecules of wood, coal, or petroleum remain there indefinitely without gradually burning itself away?

The conservation law requires that energy in a given state will remain in that state until its equilibrium is disturbed. After all, heat is nothing but molecular motion; as long as the cellulose or hydrocarbon molecules are moving at a normal speed, they will retain the energy that caused them to combine unto all eternity.

It is not until a rise in temperature—that is, an increase in the speed of the molecules—occurs that the energy is given off. Sometimes this is brought about very gradually, as when the sun shines for a long time on a heap of dry cotton waste; the molecules on the surface gradually travel faster and faster until they reach a point at which oxygen can combine with them. Result: spontaneous combustion. At other times, the energy release is almost instantaneous, as when a spark ignites the gasoline-air mixture in a cylinder head. Incidentally, the automobile is an excellent instance of the transformation of molecular into mechanical energy.

22. *Rust*

Now that we have learned something about combustion we can better appreciate how widespread in nature the oxidation reaction is. It is not limited to compounds containing carbon, nor even to compounds at all. The atoms of some kinds of metals oxidize very easily, others less so, and some not at all. Such oxidations can be considered as inorganic combustion reactions,

since carbon atoms are not involved; but they all require energy input.

Iron atoms oxidize with little energy—ordinary sunlight is sufficient. The product, of course, is rust, or iron oxide (Fe_2O_3). The heat necessary to form this compound is trapped in it, and is released if the rust is reacted with hydrogen:

$$\underset{\textit{iron oxide}}{Fe_2O_3} + \underset{\textit{hydrogen}}{3H_2} \rightarrow \underset{\textit{iron}}{2Fe} + \underset{\textit{water}}{3H_2O} + \underset{\textit{energy}}{\Delta}$$

This process is known as *reduction,* which in chemical parlance means removing the oxygen from a compound, and is the reverse of combustion. Of course the natural formation of rust is an extremely slow process, and so is the evolution of heat when it is reduced with hydrogen. It is none the less a combustion reaction, once more illustrating the application of the law of energy conservation. Other metals, such as lead, manganese, zinc and tin require extremely high temperatures for oxidation, such as those obtained with an acetylene torch.

23. *Thermite*

But we have not yet finished with the usually innocuous rust. Mixed with finely ground aluminum powder, it is the chief constituent of the *thermite bomb,* and also has many industrial uses. Aluminum is a metal which yearns so ardently to combine with oxygen that it will do

so on the slightest pretext. In fact, aluminum cooking utensils are covered with a film of aluminum oxide which is formed at room temperature. When heat is supplied to a mixture of aluminum and iron oxide (rust) particles, the aluminum avidly seizes the oxygen from the oxide, thus "reducing" it. The reaction is so violent that a tremendous amount of heat is liberated. A thermite incendiary bomb can reach and maintain a temperature of 5000° F, sufficient to penetrate a six-inch plate of deck armor. As considerable heat is required to start the reaction, thermite is usually ignited by a charge of magnesium. The "oxidation-reduction" reaction involved in the burning of thermite is:

$$2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe + \Delta$$

It is evident in this equation that the oxygen atoms have been transferred from the iron to the aluminum atom; in other words, the aluminum is oxidized and the iron oxide is reduced. The excessive heat formed is caused by the tremendous *rapidity* of the reaction: the faster the atoms move, the higher the temperature produced.

Incendiary bombs are also made from magnesium, another metal which yields terrific heat when oxidized. During the war, thin sheets of magnesium were dropped on forests in Germany in the hope that the sun's heat would ignite them and start fires.

24. *Explosive Compounds.*

IN THE FOREGOING sections it has been explained in some detail that combustion involves two phenomena (1) the chemical union of oxygen with carbon atoms to form carbon dioxide and water, and (2) the liberation of more or less energy, the amount depending on the nature of the fuel. So it will hardly come as a surprise that explosions are basically combustion or oxidation processes, although they have a couple of extra "wrinkles".

The first of these is that the molecules of most high explosives contain the element *nitrogen,* usually in close association with oxygen. Nitroglycerine, for example, is composed of carbon, nitrogen and oxygen: its chemical formula is $C_3H_5(NO_3)_3$; trinitrotoluene, the familiar TNT, contains the same three elements in different proportions: $CH_3C_6H_2(NO_3)_3$. Notice that the nitrogen in these compounds is so closely bound up with the oxygen that the four atoms move about together and actually behave as if they were a single atom. This fact is indicated by enclosing the NO_3 in parentheses. Such a composite atom is called a *radical.*

Now at ordinary temperatures nitrogen is quite inactive; it dislikes to combine with other elements unless forced to do so by application of heat. The best illustration of this fact is that the air is a mixture of one-fifth oxygen and four-fifths nitrogen; yet, fortunately for us, the two

never unite into (NO_3) radicals, but remain entirely separate. The combination does occur in the vast Chilean nitrate deposits, in the form of sodium nitrate, from which nitric acid (HNO_3) is made. It can be made synthetically; reacted with glycerine it forms nitroglycerine and with toluene, trinitrotoluene.

Nitrogen makes up for its usual inertia by being ultraenergetic at high temperatures. Explosive compounds are more or less unstable and require only a jolt or a blow for detonation; when this occurs, a furiously rapid oxidation, or internal combustion, takes place and an excessive quantity of energy is emitted. Result: explosion. Chemically, the oxygen atoms in the explosive are torn from the nitrogen atoms and unite with the carbon and hydrogen. This fact brings us to the second "wrinkle" of explosives.

25. *Gas Expansion*

THE CARBON DIOXIDE and water are released as gases, together with gaseous nitrogen compounds. Here is where the explosion gets in its demolition effect: the force with which these gases expand is so tremendous that it can flatten any object within range; the area over which it acts depends, of course, on the kind and quantity of the explosive. The gases are expanded *almost instantaneously* by the terrific heat resulting from the decomposition of the molecules of nitroglycerine or TNT. This is why any

Press Assoc., Inc.

Figure 6. *The atom bomb attack on Hiroshima left this mass of twisted steel and this gutted building standing in acres of desolation.*

explosive is more effective when enclosed in a metal container like a bomb-casing; the less space the gases have to expand in, the more shattering will be their effect.

It is an established law of physics that any gas expands 1/273 of its volume at 0° C for every 1° C rise in temperature. Let us suppose that the gaseous combustion products of a given quantity of high explosive would normally occupy one cubic foot of space at 0° C. If the temperature created by the combustion were 1500° C, it would mean that the one cubic foot of gas would undergo an almost instantaneous expansion of

six and a half times; in other words one cubic foot must expand to occupy 6.5 cubic feet in "nothing flat". Now the force exerted by a moving body, including an expanding gas, is inversely proportional to the time in which it acts; if the time is zero, the force exerted is theoretically infinite. Although an explosion takes place with extreme rapidity, it none the less requires some minute fraction of a second. If the time were twice as long, the explosion would lose a large part of its destructive effect, which to repeat is due to the tremendous rate of expansion of the gases formed. When one cubic foot of a gas is forced to increase to 6.5 times its volume in something like one-hundredth of a second, something is going to get broken!

Naturally the violently expanding gases push the air out of their way as they go and simultaneously heat it so that it too expands. The result of this pushing and heating is a compression wave, radiating from the center of the explosion, which is strong enough to buckle walls and break windows at quite remote distances. It also severely, and sometimes fatally, compresses the lungs and blood vessels of those who chance to be in the way.

As we have seen in the case of thermite, it is perfectly possible to have a high temperature *without* an explosion if the material is allowed to burn freely in air. Thermite, of course, produces no gases; but dynamite, which is a mixture of nitroglycerine and a porous clay, can be

Press Assoc., Inc.

Figure 7. *Atomic bomb destruction in Hiroshima. The ravaged building was once a theater.*

ignited in the open air and will burn as placidly as a stick of wood, since the formation of gases is relatively *slow* and there is plenty of room for them to expand. A sudden shock or blow, however, disturbs the equilibrium of the nitrogen atoms, and detonates the explosive with destructive results. Nitroglycerine and dynamite are much more shock-sensitive than TNT, which is usually detonated with a small charge of dynamite or by the impact of a rifle bullet.

26. The Nature of Gases

So IMPORTANT IS gas expansion in the action of most explosives that it must be clearly understood just what a gas is. Essentially it is that state of matter in which there are comparatively

few molecules in a given volume. The molecules may be of many substances, but by far the most common ones are oxygen, nitrogen, carbon dioxide and water vapor. How many is "comparatively few" molecules? Well, it has been definitely found that one cubic centimeter of any gas contains about 2.7×10^{19} of them—an utterly stupendous number! In ordinary notation it would be represented by 27 followed by eighteen zeros. As gases are far less dense than liquids and solids it is apparent that the number of molecules in a cubic centimeter of a solid or liquid explosive is still more stupendous.

The molecules of a gas, being made up of atoms, are rushing around at velocities up to a mile a second, colliding with and jostling one another much more vigorously than commuters in a subway rush. The lighter molecules, however, travel faster than the heavier ones—a fact of great importance in the development of the atomic bomb. A hydrogen molecule is said to take part in about ten billion collisions a *second* at normal temperature and pressure; both its speed and its frequency of collision increase rapidly as the temperature is raised. If the gas is confined, considerable pressure is exerted on the walls of the container by the incessant pounding of the molecules. As the pressure rises with temperature and the gas expands, the strongest container is likely to burst if excessive heat is applied.

27. *Mass vs Weight*

IN DEALING WITH problems involving physical energy, especially when molecules and atoms are concerned, scientists are obliged to use strictly accurate values. The commonplace term "weight" is all very well for vegetables in the grocery store and for private avoirdupois determinations on the bathroom scales, but it is not universally valid. Every body (human included!) is attracted toward the center of the earth by gravity; *weight* is merely the expression of the extent of this attraction under normal conditions, that is, at sea level. A chunk of iron which has one weight on the ground near the seashore, will have somewhat less weight at an elevation of 40,000 feet in an airplane; as its distance from the earth's center increases its weight decreases, until it theoretically approaches zero away out in space where it is free from the earth's attraction.

The *mass* of a body is defined as the quantity of matter it contains. Obviously this value cannot be affected by its position relative to the earth, and is independent of gravity: it would have the same mass no matter what its distance from the earth's center. Mass has nothing to do with size, volume, or shape; but since the pull of gravity is directly proportional to mass, it can be expressed in the same units as weight, as long as the determinations are made at or near sea level. As we shall see later, the mass of a body

increases with its velocity, though this increase becomes measurable only in the case of molecules or atoms moving at terrific speed.

28. *Potential Energy*

GASES ARE COMPOSED of an astounding number of molecular particles moving at tremendous speeds. What is the implication of this fact for the destructiveness of explosives? To leave the explanation with the statement that it is due to expanding gases would be telling only half the story. To say that a gas expands is just another way of stating that a lot of molecules are going somewhere in a bigger hurry than usual. What gives it the force necessary to blast concrete structures into rubble and rip even the strongest metals out of shape? How can anything as lacking in solidity as gas wreak such havoc, no matter how fast it expands? One or two principles of physics will explain what happens.

If a mass of 10 pounds is lifted 10 feet high, the work done is 10 × 10, or 100 foot-pounds. The mass has thus acquired a *potential energy* equal to the work done upon it. "Work" in the physical sense is defined as force times the distance through which it acts. When this mass is released, it will fall to the ground, and at the moment of impact will give back the energy originally imparted to it—namely 100 foot-pounds.

It is obvious that a rapidly moving body will have considerable capacity for doing work—

that is, it will have energy. What is not so obvious is the *quantity* of energy it will deliver—for this is surprisingly large. An automobile running at 40 miles an hour, a rifle bullet traveling 3,000 feet a second, a baseball falling from a height—all are familiar instances of bodies containing energy, which they transfer to any object that stops them: the automobile's is taken up by the brakes and the road surface; the bullet's by the target; the baseball's by the fielder's body.

29. Kinetic Energy

The energy of a body in motion is called kinetic energy, and it merely represents a return of the work previously done upon it. The potential energy of a 10-pound weight resting on a shelf 10 feet high is exactly equivalent to the kinetic energy, or impact, with which it will strike the floor when it falls. This is another instance of the omnipresent law of conservation of energy. The heat and light trapped in our molecule of methane were forms of potential energy, which were transformed into kinetic energy during combustion.

Kinetic energy depends on the *mass* of the body and the *speed* with which it moves. The surprising feature of it is that not simply the speed, but the *square* of the speed is involved. The classic formula for computing it is:

$$\textit{Kinetic Energy} = \frac{mv^2}{2}$$

which means that kinetic energy is equivalent to one-half the product of the mass (m) and the square of the velocity (v). It is highly important to grasp the significance of "velocity squared". Without going into mathematical details, this relationship of mass and speed shows, for example, that doubling the speed of a car produces not twice but *four times* as great a kinetic energy; similarly, increasing the speed of a bullet by a factor of three gives nine times as much kinetic energy. By the same rule, raising the speed of a molecule from one to ten feet a second would cause it to acquire a one-hundred fold impact energy.

The above equation accounts for such peculiar behavior of matter as a straw being driven into a tree trunk during a cyclone. Here the mass is extremely small, but v^2 is so tremendous that the result is a kinetic energy of amazing value. On the other hand, take the case of a heavy locomotive striking a bumper when moving only two or three miles an hour: although v^2 is very small, the high mass factor gives an energy more than sufficient to demolish the bumper.

30. Why Explosions Demolish Buildings

Going back now to the speeding molecules of a gas and applying this important principle, we can readily see that the heat generated by the combustion of an explosion accelerates a mole-

cule to a terrific speed, which enables it to deliver an appreciable impact to anything it strikes.

It is difficult and unnecessary to make actual computations of this force. Let us assume that under the conditions of an exploding charge of TNT each molecule of the expanding gases has a minute kinetic energy—minute, that is, in terms of objects of visible size, but huge in comparison with the mass of the molecule. Recalling the horrendous number of molecules in a cubic centimeter of a gas (2.7×10^{19}), we can see that it is easily possible for about five hundred *billion* of them to strike one square centimeter of the side of a building simultaneously. Even though each molecule has a microscopic impact force, the total kinetic energy delivered over an area of *one square centimeter* will be gigantic. Is it any wonder that the props are knocked from under the strongest building?

Thus the demolition effect of all explosions is basically caused by the impact of countless billions of molecules moving at an almost inconceivable speed, which in turn depends on the energy released by the explosive in the form of heat. So far, we have seen that this energy results from oxidation reactions—the breakdown and rearrangement of *molecules*, which also stimulates the atoms so greatly that they give off light, a slightly different form of energy. The energy of the atomic bomb comes from within *atoms*. To learn how this is possible we

shall have to analyze the concept of energy more thoroughly, and then examine the structure of the atom.

31. The Sun

Thousands of times larger than the earth, the sun is a mass of condensed gases or liquids, the temperature of which ranges from about 10,000° F on the surface to nobody knows what in the interior. Only the minutest fraction of the energy given off reaches the earth; most of it is dissipated into space. Nevertheless, as we have already seen, the earth receives about 1.5 horsepower of solar energy per square yard of its surface; physicists have calculated that the total radiant energy striking the earth is about 230 trillion horsepower. What sort of chemical combustion can be going on in the sun to maintain such tremendous energy century after century? Why does the sun not burn itself up in a few years? In replying to these questions we shall have to become adjusted to thinking about energy not in terms of moving bodies like bullets, automobiles, or even molecules, but as an alternate form of mass.

The gases and liquids which form the sun probably are composed of atoms only; it does not seem likely that molecules could exist at such temperatures. Scientists have identified almost all the elements in the sun by their spectra; indeed helium was found there before it was located on earth. There is no fuel or any chemi-

cal reaction known which could account for the sun's heat and light. The process is not one of combustion at all, but of the *conversion of mass into energy,* just as occurs in the atomic bomb. Yet this conversion is so slow, and the energy content of mass so great that the size of the sun has not decreased measurably in the last 5,000 years. If any such chemical reactions as explosions or rapid oxidations were responsible for its heat, the sun would have consumed itself centuries ago.

32. *Mass-Energy Transformation*

THE NEW APPROACH to the energy problem just referred to is one which physicists were slow to accept forty years ago, but which has proved to be correct. It is one component of the famous theory of relativity advanced by Albert Einstein in 1905 and seconded by such brilliant scientists as Max Planck, Niels Bohr, and Ernest Rutherford. The conclusion that Einstein reached in regard to mass and energy was that each can be converted into the other—that is, that mass is merely a form of *condensed energy,* and will be transformed into it if enough force is available. Closely related to this concept is the fact that the faster a body is moving—that is, the greater its kinetic energy—the greater will be its *mass.* It is as if mass were the *alter ego* of energy—a marvelously subtle distinction!

This startling development in twentieth-century physics—the relativity theory and its impli-

cations—is the only tenable explanation of the inexhaustible quantity of radiant energy in the sun. What is taking place is a continual *disintegration of atoms,* each of which can deliver several million electron volts of energy. Thus an almost eternal source of mass-energy is available in the sun; but so vast is the quantity extracted from each atom that the total mass of the sun decreases imperceptibly from century to century. It has been stated, however, that the sun loses four million tons of mass a second by this conversion of mass to energy; yet even at this rate it would take 15 million million years to radiate itself out of existence!*

Einstein expresses the true magnitude of the amount of energy contained in a given mass by a variation of the kinetic energy formula given in a preceding section. Einstein's one constant in a universe of relativity is the speed of light (186,000 miles a second). All values must be stated in terms of this constant. So his energy equation (possibly the most important in all science) is:

$$E = mc^2$$

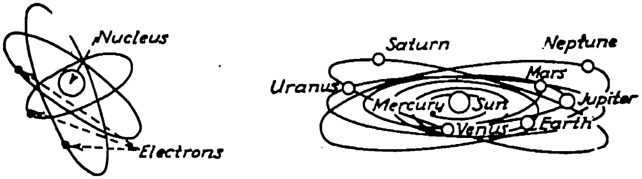
where m is a given mass and c^2 (corresponding to the usual v^2) is the square of the speed of light. According to this, the kinetic energy released by *one gram* of mass is about one sextillion (1,000,000,000,000,000,000) gram-centimeters!*

*Bazzoni, C. B., "Energy and Matter", p. 94, N. Y., The University Society, 1934.

This phase of the subject is of crucial importance, but it is difficult to present intelligently until we have more facts at hand as to how radiant energy is constituted. One additional point can be made, however: even energy has some mass. It is actually possible to weigh sunlight! We therefore must regard energy as the basic entity of the universe; sometimes it is in the highly condensed form of material substance, at others it is in a relatively fluid form, like sunlight. Just as a solid may be a highly viscous liquid, like glass, which will become fluid or even gaseous when heated, so the energy locked up in bodies of matter may be converted to a volatile state, best exemplified by radiation.

33. Inside The Atom

We have gone about as far in explaining the nature of atomic energy as is possible without knowing something of the structure of the atom

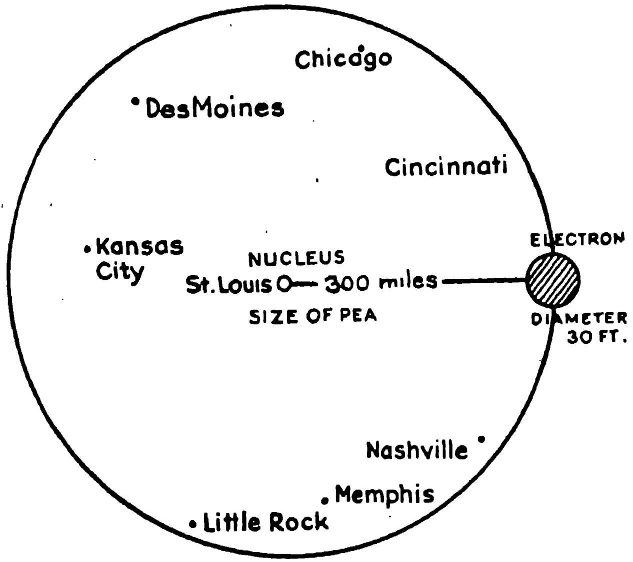


From Hawley, "Seeing the Invisible" (Knopf)

Figure 8. *The atom is built on the same plan as the solar system.*

itself. In previously describing the nature of atoms, it was mentioned that they can be divided

into still smaller particles which are fundamentally electrical in nature. Hackneyed indeed is the comparison of the internal workings of an atom with the sun and the planets passing around it in regular orbits; yet no other simile seems quite adequate. The atom is a minute solar system. At its center is a core, called the nucleus, which corresponds to the sun; revolving around it at high velocities are one or more electrons, at distances which are relatively enormous.



From Bazzoni, "Energy and Matter", University Society, New York

Figure 9. *Rutherford's concept of a hydrogen atom. (See text for explanation.)*

A general idea of the relative sizes and distances is given in the diagram above worked out by Sir Ernest Rutherford, a pioneer in modern physical research. It shows how much area

an atom of hydrogen would cover if the nucleus were enlarged to the size of a pea, which would be billions of times larger than it actually is. If this nucleus were placed at St. Louis, the electron would become thirty feet in diameter, and its orbit would pass through Chicago on the north and Little Rock on the south—a distance of 600 miles! Although such diagrams as this are useful, they should not be interpreted too literally. Physicists now admit that they cannot represent in any definite way precisely what the inside of an atom looks like. Moreover, this diagram has one great shortcoming: it gives no idea of the *mass* relationship between nucleus and electron. Although much smaller in diameter than the electron, and incomparably smaller than the whole atom, the mass of the nucleus is 1,835 times that of its electron! For all practical purposes then, the mass of an atom is determined by its nucleus.

34. Electrical Balance

What holds the atom together, and keeps the speeding electron from darting away on its own? This question can be understood by asking another which is analogous to it: What holds the earth and the other planets in their regular courses? Everyone knows that this is the force of gravity, which is really an expression of the *attraction*, or pull, which exists between any two bodies in space: the larger the body, the

stronger the pull. Much the same is true within the minute solar system of the atom, except that the nucleus attracts the flying electron by means of electrical rather than gravitational forces.

Besides being vastly heavier than the electron, the nucleus always carries with it one or more charges of positive electricity; the electron, however, is just a fleck of negative electricity. The electrical forces in an atom obey the universal rule that particles having the same kind of electrical charge, whether positive or negative, repel each other, and those having opposite charges are mutually attracted.

It would seem from this description that most of the interior of an atom is empty space, similar to that between the planets and the sun. To our limited perceptive faculties, that is true; yet it is obvious that the electrical forces just mentioned are not too different from the gravitational force in the solar system. The space between nucleus and electron therefore cannot be "empty"; it is a field of force, or energy, and we know that all energy has some qualities of mass. There can be no such thing as absolute emptiness in Einstein's universe!

Every atom is electrically *neutral* by instinct: that is, its tendency is to maintain its neutral balance at all times. The number of positive charges on the nucleus, whatever it may be, is normally just equal to the number of negative charges, or electrons. As the units of positive charge range from one to 92, so does the

number of electrons. There are plenty of instances in chemistry where an atom loses an electron to a rival atom, and thus is left with a small numerical excess of positive charge; or it may gain an electron in the same way, and become overbalanced on the negative side. This is known as ***ionization***. Though it is of no particular importance in this discussion, we shall need to refer to it later. Notwithstanding this tendency to lose or gain an electron, the atom prefers to be in exact electrical balance, if one can attribute instincts to inanimate matter.

35. *Protons*

HAVING LOOKED AT the atom as a whole, let us get a closeup of each of its three component parts individually. Protons are the first candidate for attention. The hydrogen atom is the simplest, as well as the lightest, of all. It is the only one whose nucleus is composed of a single proton, or positively charged particle; in the single case of hydrogen the nucleus and the proton are identical. This hydrogen proton has often been used as a "bullet" for smashing other atoms. The situation in respect to the rest of the elements is not so simple, however. Their nuclei are not single particles but aggregations of particles bound together by powerful forces and normally in a condition of equilibrium.

Each proton is positively charged, like the hydrogen nucleus. Therefore the entire nucleus

is likewise positive, and exerts a very strong repulsion force on any positively charged particle that tries to enter it. The number of protons in the nucleus of any atom is designated by its *atomic number,* and this number also indicates its sequence position in the Periodic Table. Thus hydrogen has an atomic number of 1, helium 2, oxygen 8, and uranium 92, which means that these atoms contain respectively 1, 4, 8, and 92 protons. Do not be alarmed by the statement made a few lines back that the number of positive charges is equal to the number of electrons. As a matter of fact the atomic number stands for *either* protons or electrons since there must be the same number of both in a balanced system. It is equally true that the elements just named have 1, 2, 8, and 92 electrons.

36. Neutrons

WITH THE SINGLE exception of hydrogen, all atomic nuclei are composed of protons and neutrons. The great virtue of the neutron is that it has no electrical charge; this enables it to move about in the vicinity of powerfully charged bodies like protons without let or hindrance. It can penetrate "walls" of electrical repulsion without effort, and is adept also at penetrating almost all substances except those of low atomic weight, like water, carbon and paraffin.

The number of neutrons in an atom is found by subtracting its atomic number from its

atomic weight. Helium, as just mentioned, has an atomic weight of 4 and an atomic number of 2, indicating the presence of two neutrons together with the two protons in its nucleus. The helium nucleus, incidentally, is of extreme importance in the history of nuclear disintegration, for it was the first particle to be hurled at other nuclei. In the case of oxygen of atomic weight 16 and atomic number 8, there are, of course, 8 neutrons.

How can we account for the existence of neutrons? Apparently they are a combination of a proton and an electron, which explains the absence of an electrical charge. Since such a union would mean a negligible gain in mass, and since it was formerly fairly well established that electrons are present in atomic nuclei, this explanation is undoubtedly correct. Neutrons are a very recent acquisition of the physical chemist; they were discovered in 1932 by J. Chadwick at the Cavendish Laboratory in Cambridge, England. We shall see later how this was done.

The discovery of neutrons gave a tremendous boost to research on atomic disintegration, for their electrical neutrality makes them ideal projectiles. However, the only means of obtaining a supply for this purpose was to release them from their nuclear prisons by bombardment with other types of projectiles, such as the helium nucleus. The first neutrons were obtained in this way.

It may be wondered why atoms themselves cannot be used as bullets, since they too are neutral electrically. This is chiefly because they are incomprehensibly larger than neutrons (whose mass is only 1.00), and also because atoms involve the complication of a swarm of negative electrons which would produce disturbing radiation effects. There is no known method

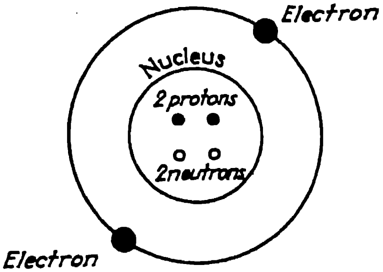


Figure 10. *Helium nucleus (also called an alpha particle).*

of giving atoms high velocity; the high speed of neutrons is caused by their expulsion from the nucleus.

37. Nuclear Forces

A FEW PAGES back we postponed further discussion of the all-important interconversion of mass to energy until we had become acquainted with the atomic nucleus. Now that this has been done, it is not difficult to show the truth of Einstein's theory, which is surely the most important single principle of modern physics. We have seen that the protons and neutrons comprising

the nucleus of an atom are held powerfully together by forces, the precise nature and mechanism of which are still uncertain. Hans A. Bethe of Cornell has stated* that "the binding force that holds atomic nuclei together and keeps the universe from exploding is a powerful attraction between protons and neutrons in the atomic nucleus." This attraction implies the presence of a high degree of potential energy; that is, work must have originally been done on the system to get it into the form of a nucleus.

Now if energy is really just an aspect or alternate form of mass, it should follow that the sum of the masses of the individual components of the nucleus is slightly more than the total mass of the nucleus as a whole. In the first case we should expect the binding energy to appear as part of the mass of the protons and neutrons; in the second case this mass is in the form of energy. Let us see how this works out for a helium nucleus. Its atomic weight, or mass, is 4 and its atomic number is 2; within the nucleus are 2 protons and 2 neutrons. Here we must use most precise weights taken from statistical tables. The sum of the masses of these particles is:

$$\underset{\textit{protons}}{2(1.00758)} + \underset{\textit{neutrons}}{2(1.00893)} = \underset{\textit{total components}}{4.03302}$$

But it is a fact that accurate determination of the mass of this nucleus *as a whole* gives

*Time, Jan. 29, 1940, p. 42. He postulates the existence of a mesotron.

4.00280, which is approximately 0.03 unit less than the sum of the separate particles.

This tiny factor of 0.03 unit is the nigger in the well-known woodpile. It accounts for the binding force that holds the nucleus together; when

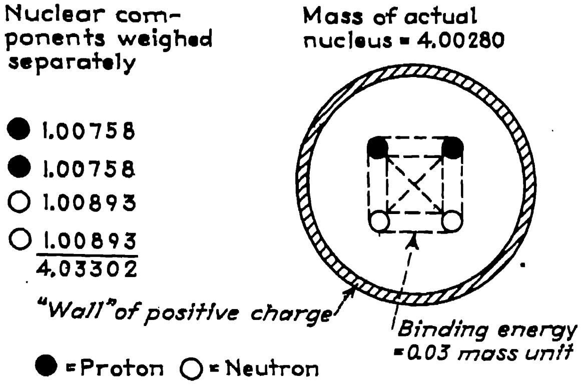


Figure 11. *Mass-energy equivalence in helium nucleus.*

the protons and neutrons united to form the nucleus, this small fraction of their mass became energy. Einstein's equivalence equation $E=mc^2$ indicates that the energy involved in that microscopic difference in mass is tremendous. As a matter of fact it means that releasing the nuclear binding energy in a gram of helium would produce 190,000 kilowatt hours of electrical energy.*

38. *Electrons*

ALTHOUGH ATOMIC DISINTEGRATION is more directly concerned with protons and neutrons

*Professor Smyth's report, Chap. I, p. 10.

than with electrons, some explanation of the latter is necessary to round out the description of atomic structure. Electrons are particles of negative electricity which were discovered by J. J. Thomson in 1897. They are much larger in area than protons, but are of insignificant mass. The electron of a hydrogen atom, for instance, contains only 1/1835th of the mass of the nucleus, or proton. On the sun's surface, most of the gases exist in the form of "stripped" nuclei from which the electrons have been torn away by the terrific heat.

The orbits in which the electrons travel around the nucleus are often thought of as "shells" by physical chemists. The more complicated atoms have as many as seven such shells, each of which contains different numbers of electrons, although the heavier elements invariably have eight in the second shell. As the shells are not in the same plane, the composite representation of a complex atom looks something like the wound core of a baseball, with irregular loops of loose thread encircling it. The electrons in the shells are aptly called *planetary* electrons; those in the outermost shell, which govern the chemical combining power of the atom, are known as *valence* electrons.

The planetary electrons can rather easily be torn loose from their nuclei altogether when struck by electrons from an external source; this is what happens in a neon tube. If the force is great enough, the attraction between the elec-

trons and the nucleus is outbalanced and the electrons fly out into space—free! It is as if you tied a golf ball to a rubber thread and swung it around your head at constantly increasing velocity. The ball would describe ever-widening circles, and finally the thread would break and the ball would go shooting off at a tangent. Electrons are released in this manner from heated cathodes in vacuum tubes, which are the very soul of the electronics industry.

Tearing electrons away from their nuclei, as just described, does *not* constitute atom-smashing. It is the *nucleus* that is involved in atomic disintegration; in fact the process should properly be called *nuclear disintegration.* The "stripped" atoms on the sun were not formed by disrupting the nuclei but by shucking off the electrons, leaving the nuclei to roam around alone.

39. Photons

About 1913 the Danish physicist Niels Bohr propounded a variation of Rutherford's ideas of atomic structure, which we have just described. Ten years previously Max Planck had suggested a theory of light that ran counter to prevailing ideas—namely, that light is not a "continuous flow" phenomenon, but a discontinuous one, and that it is radiated in the form of clots of radiant energy which he called *quanta,* though today they are more generally

termed *photons*.* Bohr applied this theory to the electron-shell concept. According to him, the distances separating the planetary electrons from the nucleus are not fixed; if the temperature increases, the electrons so activated jump from an inner orbit to the one next farther out. This process continues as long as the atom is absorbing energy; as a result, the atom expands, for the electrons in the outer shell are much farther from the nucleus in the "excited" than in the normal state.

We know enough by now to realize that the law of conservation of energy demands that any energy acquired by an atom must eventually be given off. Bohr asserted that when the energy input slackens or ceases, the excited electrons drop back into their original positions, *each one giving off a photon (or quantum) of radiant energy as it does so.* It is these photons, emitted in unnumbered billions by the sun, the stars, a hot tungsten filament, or a stick of burning wood, that constitute what we know as *light.* As a matter of fact, quantum radiation furnishes a portion of the energy obtained from combustion, previously discussed.

40. Electrons vs Photons

EXACTLY WHAT IS the difference, then, between an electron and a photon? It is difficult to say

*Planck's famous equation for the energy content of a quantum (photon) is $E = h\nu$, where h is a universal constant and ν is the frequency of the radiation.

specifically. Electrons are bits of negative electricity which have a definite mass and are therefore material particles. Photons are bundles of radiant energy which also have mass, and behave so much like particles that they also may be considered material bodies. Physicists have had a long struggle over this problem, and even now their ideas are far from clear-cut. There are points of difference between electrons and photons that are hard to reconcile; for example, photons, being radiant energy units, travel with the speed of light, or 186,000 miles a second. Electrons in the free state have been made to go as fast as 160,000 miles a second, but their pace is considerably slower than that under normal energy conditions. An electron may act like a photon in some ways, just as a photon is known at times to act like an electron. The important fact is that the hair-splitting difference between these Janus-faced particles makes it easier to see how similar matter and energy are and how readily one can be transformed into the other.

41. Energy

WHEN HUMPTY DUMPTY was trying to explain the meaning of "toves" he had to define them as "something like badgers—something like lizards —and something like corkscrews." It is equally difficult to present a definite conception of what modern physics means by *energy*. Yet an attempt should be made to do so because of the

fundamental and all-embracing nature of the phenomenon and its bearing on the atomic bomb. We know that mass is merely a form of potential energy, which *becomes kinetic energy on impact;* but kinetic energy itself has some mass. Einstein proved that the mass of a moving particle increases in proportion to its speed, until at the velocity of light it becomes theoretically infinite; potential energy therefore tends to revert into mass.

We have seen that radiant energy is given off in the form of photons, and that these are separate, distinct particles. Sunlight is a rain of photons. Yet photons are not wholly devoid of mass, nor is any other form of energy. Light, then, may be considered as "liquid" energy, as opposed to the "solid" energy represented by material bodies. In fact, mechanically speaking, light (radiant energy) has many of the properties of a liquid in spite of its particle structure; chief among these liquid properties is its *wave motion.*

How can energy be a solid and a liquid too? We might draw a rough analogy between photons, or Max Planck's energy quanta, and a load of sand being dumped over the tailboard of a truck. The sand consists of granules corresponding to photons; yet en masse they flow like a liquid. Newton's mechanics had no means of dealing with such fine particles in fluid motion —indeed their dual behavior was not realized until Planck proposed his quantum theory.

Radiant energy then is made up of concentrates of energy which are distinct entities, yet behave in some respects like liquids. Energy is thus *both* continuous and discontinuous simultaneously, depending on whether one regards it from the wave-motion or the particle viewpoint. The same in effect is true of all other energy forms; they are all aspects of the one universal entity, either highly condensed, as in solids, of medium condensation, as in nuclear binding forces, or extremely "thin", as in light.

It is hard to translate such ideas into comprehensible analogies, because they are so unlike common experience. Scientists are abandoning schematic models of atomic structure for this reason; the revolutionary ideas of Einstein and his followers have made a literal representation of these phenomena impossible. The human mind is at a loss to visualize exactly what the inside of an atom looks like—there are too many unimaginable things happening. Nor can it picture how an apparently solid particle can suddenly turn into disembodied radiation. Yet that is exactly what it does and, as we have seen, the transformation can be evaluated mathematically. It is to mathematics, indeed, that we must look for the answer to this and other questions raised by Einstein's concepts. No matter how impossible they seem to the earth-bound imaginative and reasoning powers of man, they result from sheer mathematical necessity. And we just about have to leave it at that.

However, there is solace for us of ordinary mental stature in the thought that it is not always necessary to grasp the intricacies of a fact in order to use the fact. For example, we all know and make almost daily use of the fraction one-third, which is a specific and measurable quantity; yet it is impossible to visualize *exactly* in the form of the continuing decimal 0.000333+. To put the matter another way, it is not quite fair to say, as the Red Queen did to Alice, that you can't do addition if you lose count when asked to add one and one and one and one and one and one and one and one and one and one. The average intellect has to deal in counters that are familiar to it, arranged in a comprehensible manner. But nature declines to be so accommodating. The intricate mathematic concepts which express the conversion of mass into energy and back again can safely be left to the super-duper physicists; but the truth which they state can and should be appreciated by everyone.

42. *At Gibson Island*

For some years now a summer conference on technical subjects has been conducted at Gibson Island in Chesapeake Bay. Scientists and students from leading universities and industrial laboratories attend from week to week, and are addressed by experts in the various fields. The sessions are held in a comfortable dormitory building. After the lectures each evening the

groups usually split up, some remaining to discuss the lecture and ask questions of the speaker, others adjourning to the nearby clubhouse, which has an adequate bar, for mint juleps and other soothing concoctions.

On one occasion the late Dr. Thomas Midgley was in attendance. A scientist of international reputation, he will long be remembered not only for his invention of the tetraethyl lead treatment of gasoline and of highly successful synthetic refrigerants, but for his genial and gracious personality, his scintillating intellect, and his unfailing sense of humor. It was a particularly hot evening, the lecture had been long, and the chairs had been getting extremely hard. When the discussion was about to begin, Dr. Midgley arose and, looking around at the group, remarked to the man next to him, "Well, shall we drink with the topers or stay here with the isotopers?"

43. Isotopes

In a comedy gag that has been used time and again in the movies, a character who has just come into a fortune is seen busily counting his wealth. For some time he goes on mumbling "400, 500, 600, 700 . . ." till with a disgusted expression he whisks out a bill and throws it away, disdainfully remarking, "How did that five get in there?" And so it is with isotopes!

An isotope is an atom which is identical with all the other atoms of its element, except that its atomic weight is different. For example, one out of every 5,000 atoms of hydrogen has an atomic weight of 2.016 instead of 1.008. This odd atom has a neutron in its nucleus as well as a proton; it is popularly known as heavy hydrogen, and the water containing it as *heavy water*. The heavy atom itself was isolated by Dr. Harold Urey by repeated electrolysis, by which he was able to sort out the rare heavy atoms. This "chemical twin" of the hydrogen atom was christened a *deuteron,* and its compound with oxygen *deuterium oxide* (D_2O).

Particles such as these, which have a different atomic weight from their brother atoms but are like them in all other respects, have been named *isotopes,* which means "having the same position" (in the Periodic Table). It is most important to become familiar with them for two reasons: one is that the hydrogen isotope, or deuteron, being twice as heavy as a normal hydrogen nucleus, is a most effective "bullet" to shoot at other nuclei; the other is that one of the most effective sources of atomic power is the uranium isotope U-235.

Before discussing this, however, let us look at some of the other elements. The case of hydrogen is peculiar, in that its isotopic form is exactly *twice* the mass of its normal form. In the heavier atoms, the difference between the mass of the isotope and that of the ordinary atom is much

less. Moreover, isotopes occur with considerably greater frequency in other elements than in hydrogen. An extreme case is chlorine, with an atomic weight of 35.5; it is made up of two groups of atoms, in a ratio of 3:1, the weight of one group being 35, that of the other 37. Here the isotopic atoms are almost as numerous as the normal. In the case of uranium, one isotope of atomic weight 235 is found in every 140 atoms of the standard weight, which is 238. Since the chemical properties of isotopes are identical with those of regular atoms, their discovery and segregation was of little interest to chemists. Physicists, however, welcomed them with gusto, because they opened a new avenue of approach to the structure of matter.

44. Radioactivity

The nuclei of *most* atoms are the very incarnation of stability. They refuse to be disrupted by any temperatures that can be obtained artificially, and it was not till 1919 that one of them was actually invaded for the first time. Rutherford and his contemporaries at the turn of the century were pretty well convinced that this was true of *all* atoms; when it was found that there were several startling exceptions to this principle, great was the consternation of the "classical" physicists. It seemed to them that questioning the stability and rock-ribbed permanence of the elements was like weakening the founda-

tions of the universe. Yet when in 1896 Becquerel accidentally discovered strange fogging effects produced on a photographic plate by proximity to a piece of uranium ore, and when later, after heart-breaking work, the Curies isolated radium, like the Ancient Mariner, they "could not choose but hear."

For here were two elements which were continually giving off light rays of a strange and potent kind. When these rays were passed through a magnetic field, it was found that some of them bent in one direction, some in another, and that some did not bend at all. Those that were deflected to the left were judged to consist of positively charged particles, which were later found to be identical with helium nuclei; those that bent to the right, being negatively charged, were undoubtedly electrons. The rays that shot straight out, being uncharged, were found to be a most unusual kind of light, of a perfectly unheard of wave length, and of such tremendous penetrating power that they could drive through 6 inches of lead! The positive helium emanations were imaginatively designated alpha particles; the stream of electrons, beta particles, and the formidable light ray, gamma radiation. The phenomenon itself was called *radioactivity*.

45. *Natural Atomic Disintegration*

WHAT DID THIS persistent emanation mean? Rutherford saw at once the true significance of what was going on: the atoms of the radio-

active elements *were in actual process of breaking up before his very eyes!* A whole group of elements whose atoms are radiating themselves away into protons, electrons, and photons! A discovery of the most vital significance, for it opened up the possibility of duplicating this feat artificially — of liberating the huge store of atomic energy for the service of mankind.

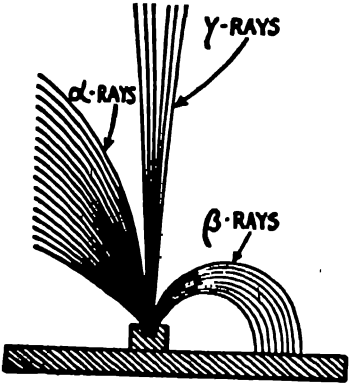


Figure 12. *Natural disintegration of the radium nucleus.*

All elements of higher atomic weight than lead are radioactive to some extent; radium is by far the most active, but uranium is also quite powerful. How fast does this disintegration of the atoms take place? Long and careful computations and experiments showed that it would take 1,750 years for half of a given quantity of radium to disappear into other forms of matter, 1,750 more years for half of the remainder to radiate away, and so on.

Radium passes through no less than eight intermediate forms before it finally becomes stable. Starting out in life with an atomic weight of 226, it slowly changes first into the element radon, and then through a series of other products of decreasing atomic weight. When at last it reaches journey's end, it is no longer either radium or radon, but an isotope of lead (atomic weight 206). Thus the two elemental decomposition products of radium and other radioactive elements are helium and lead. As its disintegration proceeds, radium emits a terrific amount of heat. It has been calculated that a single gram of radon gives off energy equivalent to two tons of coal burned in pure oxygen! But it is dissipated so slowly that none of it can be utilized in any practical way for industrial purposes.

The disintegration of radioactive elements in the Earth's crust has furnished scientists with an accurate means of computing the age of the Earth. This is done by determining the amount of lead 206 in certain types of rocks and calculating the length of time that must have been required to form it, on the basis of the figures given above. In this way the order and duration of the various geologic eras was established. The time span between the pre-Cambrian period and the present is given as 1,852 million years;* the total age of the earth is at least double that.

*Moore, R. C., "Historical Geology", p. 52, N. Y., McGraw-Hill Book Co., 1933.

46. Gamma Rays

In this resumé almost nothing has been said about the wave length of the various kinds of radiation, and it is not our intention to go into this complicated subject in detail. Nevertheless, it should be mentioned that the gamma rays of radium are of shorter wave length than any other form of radiant energy, except cosmic rays. They are about ten times as short as the shortest x-rays, which are about one two-billionth of an inch. Their tremendous penetrating power, as well as their curative power, is due to this fact. Radium cannot be safely handled unless encased in thick sheets of lead; the lead atoms contain so many electrons that even the tiny gamma rays are deflected or scattered by them. Radioactive elements are characterized by this destructive emanation, which is a form of light and therefore consists of extremely high frequency photons.

Gamma rays destroy human tissue quite rapidly, and burns resulting from them are painful and slow to heal. Fortunately, they kill malignant growth much faster than they do healthy tissue, which accounts for their wide use in cancer therapy. The absorption of radioactive emanations by the body is highly dangerous; serious poisoning and even death have resulted from prolonged exposure to the rays of uranium salts used for painting luminous watch and instrument dials.

47. *Atom-Smashing in The Stars*

TWO MAJOR INSTANCES of nuclear disintegration in nature have been described: the rapid transformation of mass to energy in the sun, and its extremely slow equivalent in radioactive substances on earth. There is still another case of this natural atom-smashing which can be detected and studied from observations made in the upper atmosphere, free from the disturbing effect of local radioactive emanations in the earth's crust. This comes to us from interstellar space in the form of cosmic rays, which are considered to result from the explosion of atoms in the stars. These rays have been found to consist of particles—whether protons or electrons has not been definitely settled—having energies in the neighborhood of 17 billion electron volts*, compared with the 200 million obtained per atom of uranium. Indeed some cosmic ray particles of as high as one *trillion* electron volts have been observed, and the hypothesis has been suggested that certain stars known as "white dwarfs" must contain elements of atomic weight approaching 25,000 in order to produce any such energy.†

There has been considerable contention among physicists as to the source and nature of these rays. Professor R. A. Millikan of the California Institute of Technology is probably the world's greatest expert in this field. He regards

---

**Time*, May 12, 1941, p. 72.
†*Science*, June 14, 1939, Vol. 90, p. 6 (suppl.).

the rays as being made up of electrons which arise from the annihilation of atoms of heavy elements in the stars. The original radiation itself probably consists of photons. It is definitely known that the wave length of cosmic rays is the shortest of any kind of radiation yet discovered, and their penetrating power is even greater and more destructive than gamma radiation. It has been reported* that cosmic rays can fight their way through 16 feet of lead, and the particles themselves (corresponding to alpha or beta radium emanation) can go through seven inches of lead.

Cosmic rays are the most abundant form of radiation in the universe, and the energy they contain is felt everywhere, even under ten feet of water. They furnish one more example of the mass-energy interconversion which plays such a dominant part in the modern concept of the physical world.

48. Artificial Transmutation

SIR ERNEST RUTHERFORD was the first to see that if a suitable nuclear projectile were available, it might be possible to bring it into such powerful contact with another nucleus that a proton would be ejected and the bombarded element changed into another element close to it in the Periodic Table. A tremendous kinetic energy would be necessary to do this, for both the projectile and the target nucleus have strong

* Bazzoni, "Energy and Matter", p. 107.

positive charges which repel each other vigorously. Rutherford availed himself of the alpha particles of radium, which are ordinary helium nuclei with a positive charge of 2; he used these because of their ready-made acceleration and their high kinetic energy of 8 million electron volts. (It now becomes obvious why neutrons, which carry no positive charge, are ideal particles to fire at a nucleus.)

Let us be sure we understand what Rutherford was trying to do. He reasoned that he could bombard a nitrogen atom with alpha particles and convert the nitrogen to an oxygen isotope, producing free hydrogen nuclei as well. How is this possible? In seeing how Rutherford figured it out we must have recourse to the atomic weights *and* atomic numbers of the elements concerned. In the equation below, which represents Rutherford's first achievement in 1919, the figure at the lower left of the symbol specifies the atomic number—that is, the number of protons in its nucleus—and the one at the upper right the atomic weight:

$$\underset{\substack{\textit{alpha}\\ \textit{particle}}}{{}_2He^4} \quad + \quad \underset{\substack{\textit{nitrogen}\\ \textit{nucleus}}}{{}_7N^{14}} \quad \rightarrow \quad \underset{\substack{\textit{oxygen}\\ \textit{isotope}}}{{}_8O^{17}} \quad + \quad \underset{\substack{\textit{hydrogen}\\ \textit{nucleus}\\ \textit{(proton)}}}{{}_1H^1}$$

By performing this experiment, Rutherford actually broke nitrogen up into hydrogen and an isotope of oxygen by knocking a proton out of it, the proton being replaced by an alpha particle. This was surely one of the most important

events in modern science. But is it the atom-smashing we are interested in? Not quite; for there is no abnormal release of energy. It differs from splitting the atom in the same way that nicking a piece from the outside of an apple with a B-B shot differs from cleaving the apple squarely down the center with a rifle bullet. Though it is now technically possible to split atoms of carbon, silicon, and other elements, by direct neutron hits, in practice this can be done successfully only with the heavy radioactive atoms like uranium. Returning to the equation, it will be noted that the sum of the atomic numbers on one side of the reaction equals the sum of those on the other, and ditto for the atomic weights. So the law of conservation of energy survived Rutherford's transmutation!

It was not until 1932 that the achievement was performed without alpha particles, right on the eve of the discovery of neutrons. J. D. Cockroft and E. T. S. Walton of Cambridge, England, thought they could attain the same result by using protons, or hydrogen nuclei, as their projectile, activated by a high voltage. They took the element lithium (atomic number 3), and planned to turn it into helium (atomic number 2). They were successful in doing so, and here is their transmutation reaction:

$$\underset{\textit{proton}}{{}_1H^1} + \underset{\textit{lithium}}{{}_3Li^7} \rightarrow \underset{\textit{2 alpha particles}}{{}_2He^4 + {}_2He^4}$$

In this case, the proton entering the lithium nucleus yields two helium nuclei, or alpha par-

ticles, each of which has a charge of 2 and an atomic weight of 4. Again both the total positive charges and atomic weights balance.

49. Discovery of Neutrons

THIS EXPERIMENT WAS the starting point of a vast amount of further work by leading physicists, not only in England but throughout the world. Many such transmutations were made, partly to explore the possibilities but primarily to find some way of producing neutrons. The existence of these uncharged particles had been suspected for some time, and now the means was at hand to find out if some nuclear disintegration would not produce them. The discovery was made by Chadwick at the Cavendish Laboratory in the same year that Cockroft and Walton's lithium experiment occurred. With alpha particles and beryllium as a target nucleus, Chadwick made the transmutation:

$$\underset{\text{alpha particle}}{{}_2He^4} + \underset{\text{beryllium}}{{}_4Be^0} \rightarrow \underset{\text{carbon}}{{}_6C^{12}} + \underset{\text{neutron}}{{}_0n^1}$$

Here is the first production of neutrons on record! Their charge is zero but their atomic weight is one, like the proton which they so much resemble. They are presumably formed in the nucleus by union of an electron and a proton caused by the tremendous internal pressure. Beryllium is an excellent source of neutrons; but any atom of a fairly high atomic weight will

produce neutrons when subjected to disruptive forces. As previously suggested, neutrons are excellent atom-smashing projectiles because of their ability to penetrate the positive charges on target nuclei. Since they have no positive charge, they are not repelled by the highly charged nuclei of other atoms.

The immense significance of Chadwick's discovery therefore is that it furnished physicists with a superior type of projectile with which to carry on their experiments. Needless to add, the discovery of a new constituent of the atomic nucleus was of first-rate theoretical importance in itself. Among the first to utilize neutrons was Enrico Fermi the Italian scientist; his experiments with uranium from 1934 to 1939 paved the way for the atomic bomb.

50. Mass and Energy Again

Now THAT WE have written actual equations showing the transmutation of one element into another, and have shown that they balance correctly, does not the same question arise as in the case of the simple combustion reaction? Where is the energy resulting from the release of two helium nuclei from lithium by proton bombardment? In a preceding section it was pointed out that a given atomic nucleus has slightly less mass when intact than the total mass of its protons and neutrons individually. The difference is accounted for by static energy, which has been proved to have mass; and it is this energy

which binds the intranuclear particles together. Specifically, in every helium nucleus the internal energy is equivalent to 0.03 unit of mass. It is certainly reasonable to suppose that, if the "wall" of positive charge on the nucleus is broken by an entering body, some of this locked-in energy must escape.

Taking once more the important transmutation of Cockroft and Walton, to be strictly in accordance with the law of conservation of energy we should express it with an energy increment:

$$\underset{\textit{proton}}{{}_1H^1} + \underset{\textit{lithium}}{{}_3Li^7} \rightarrow \underbrace{{}_2He^4 + {}_2He^4}_{\textit{2 alpha particles}} + \underset{\textit{kinetic energy}}{\Delta}$$

Arithmetical calculation shows that the total mass of the two alpha particles is 0.0185 unit *less* than the total of the proton and the lithium atom. It is known, however, that every alpha particle has a kinetic energy of about 8 million electron volts; this being the case, we are faced with the incontrovertible fact that 0.0185 unit of atomic mass (that is, the part of the total which represents the energy in the lithium nucleus) *has turned into 16 million electron volts of kinetic energy*. Application of the mass-energy equation, $E = mc^2$, to these values shows that the two are so nearly equal as to prove conclusively the truth of Einstein's predictions.

It is true, of course, that the kinetic energy released also has some mass. To visualize this we can only apply the concept previously sug-

gested. The binding forces within the nucleus are energy in a more highly condensed state, and the kinetic energy resulting from the transmutation is in a less condensed, more nearly fluid form.

51. Modern Alchemy

A word might be said about an interesting sidelight on the transmutation story. It has little practical importance either scientifically or economically, for the technique involves so much energy that the results could never be profitable. But the alchemists' old dream of making gold out of other metals has been proved possible. By the bombardment of atomic nuclei with protons or alpha particles, thus ejecting a proton or alpha particle, it had been proved that one element could be changed into another *not more than two places away from it in the Periodic Table*. Then why not make gold by disintegrating the nucleus of its nearest neighbor in the table? This is, of course, mercury. The feat was performed more to prove that it could be done than for any practical reason. Here is the reaction:

$$\underset{\textit{proton}}{{}_{1}H^{1}} + \underset{\textit{mercury}}{{}_{80}Hg^{200}} \rightarrow \underset{\textit{gold}}{{}_{79}Au^{197}} + \underset{\textit{alpha particle}}{{}_{2}He^{4}}$$

R. Sherr and K. T. Bainbridge of Harvard University carried out this reaction in 1941; the gold, however, was found to be unstable, as so much ill-gotten wealth is!

52. Deuterons

IN THE EARLY '30's the isotope of hydrogen, called deuterium, was isolated by H. C. Urey at Columbia. The deuterium nucleus or deuteron, is exactly like an ordinary one except that its atomic weight is doubled, so that it would be represented by $_1H^2$ instead of $_1H^1$. This, like the neutron, looked as if it would make an excellent projectile, for in spite of its positive charge, it has twice the kinetic energy $\frac{mv^2}{2}$ of a proton at a given speed. Deuterons were first used for atomic disintegration in the famous cyclotron of Ernest O. Lawrence at Berkeley, California.

As we have now mentioned several kinds of projectiles used to hurl at atomic nuclei, a resumé of these may be helpful. There are four of them, as follows:

Name	Origin	Charge	Approximate Atomic Weight
alpha particle (helium nucleus)	radium emanation	+2	4
proton (hydrogen nucleus)	hydrogen atom	+1	1
neutron	atomic nuclei	0	1
deuteron	hydrogen isotope	+1	2

In general it may be said that the last two are most widely used today in view of their intrinsic advantages and of the scarcity of radium and its radioactive relatives.

53. *Cloud Chamber*

Now comes a question that probably has already occurred to anyone who has read this far. If atoms are much too small to be seen in any microscope, neutrons and helium nuclei must be much smaller; how then could these investigators tell what particles their experiments produced? The answer to this sounds like more double talk, but it is another one of those subtle distinctions which arise to plague those who attempt to "popularize" science. There is a very definite difference between seeing a particle and seeing evidences of its presence. As subatomic particles are infinitely beyond the range of any microscope, scientists had to devise some way of detecting them. To do this the English physicist, C. T. R. Wilson, had invented in 1911 what he called a "cloud chamber".

The theory of this particle detector is this. It is a proven fact that water particles will condense on minute dust particles in the air to form fog. Would not a neutron or a proton be able to cause saturated water vapor to condense along its path and thus leave a trail of fog behind it? Wilson reasoned that in passing through air, a free particle such as an electron would "ionize" the atoms of oxygen—that is, it would form a path of positively charged atoms (ions) which would serve as centers of condensation for the vapor. So he constructed a chamber filled with air and water vapor, into which disintegrated fragments of the atoms are passed. As they

From Bassoni, "Energy and Matter", University Society, N. Y.

Figure 13. *Wilson cloud photo showing path of an alpha particle or helium nucleus.*

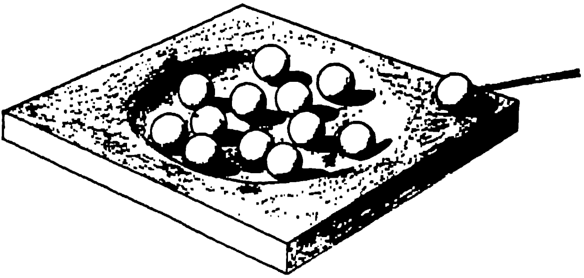
plunge headlong through the chamber, their course is marked by a tell-tale wake of fog which, when photographed instantaneously, enabled Wilson to say, "There went an alpha particle!" Remarkable pictures have been made of neutrons and other nuclear fragments* actually striking a nucleus and darting off at a tangent. A cloud chamber is an essential part of modern atom-smashing machines.

54. *A Closer Look at Nuclear Disintegration*

In the last few sections, subatomic projectiles have been flying around and scattering disintegration products right and left. It is now time to take a slow-motion picture of this ultra-rapid process and see what really happens inside a nucleus when it is invaded by an outside particle.

*The positron was first identified in this way.

It should be obvious that we are concerned here with kinetic energy: that of the alpha particle used by Rutherford was about 8,000,000 electron volts, which is about the minimum necessary to eject a neutron from the nucleus.* The situation can easily be visualized by thinking of the protons and neutrons in the nucleus as so many billiard balls lying in a shallow plate, and the impinging body as another ball driven in from the outside.* If there were no other balls



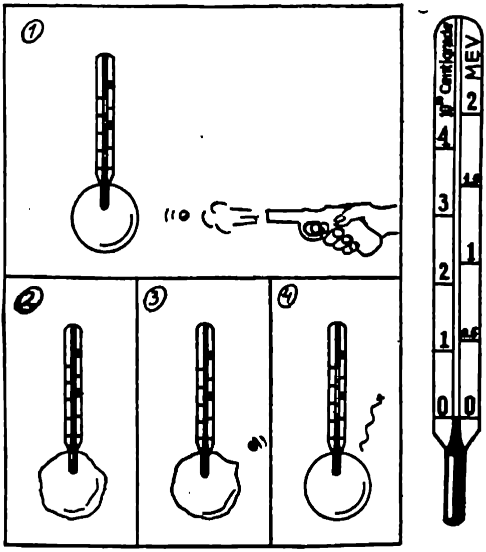
Courtesy Science Magazine

Figure 14. *Bohr's analogy of nuclear disintegration. (Explanation in text.)*

in the plate (see figure above), the entering ball would go down one side of the depression, cross the plate, and go out the other side without interference. But if there are say twelve balls in the plate, another ball coming in rapidly will distribute its kinetic energy from one of them to another. After this force has been shared by all the balls in the plate, the total may be too much for them to stand; as a result, a ball on the

*Bohr, N., *Science*, Vol. 86, p. 162 (1937).

opposite side will be jounced out. If, however, the kinetic energy of the entering ball is *not* great enough to knock a ball out of the dish—that is, if the energy content of the balls is low enough to accept additional energy without spilling over—it will remain as a thirteenth ball.



Courtesy Science Magazine

Figure 15. *Bohr's schematic representation of nuclear disintegration.*

This is a useful analogy up to a point—the point being that it gives no idea of the tremendous force holding the protons and neutrons together in a nucleus. The impact of the entering ball has to be great enough to disrupt this, at least momentarily. When an outside neutron enters at high speed, transmission of energy within the nucleus takes place, just as with the

billiard balls; but if the neutron has somewhat less kinetic energy it will *remain* in the nucleus and thus create an unstable energy state. When this occurs, the nucleus is said to "capture" the neutron.

The foregoing diagram shows a nucleus being struck by a neutron "bullet". An imaginary thermometer has been inserted in the nucleus. Before impact, the temperature is zero; in the second picture, the neutron has entered the nucleus, the temperature has risen, and the irregular shape of the nucleus indicates the commotion excited by the uninvited guest. Next, a neutron or proton is ejected to restore equilibrium, and the temperature drops. Finally, with a shudder of radiation the nucleus is at peace again, with temperature normal.

55. *Induced Radioactivity*

THIS "SHUDDER OF RADIATION" is somewhat more scientifically called *induced* radioactivity. The crude diagram in the preceding section indicates that the entering projectile ejects its counterpart on the opposite side of the nucleus almost immediately; and it is true that this does happen in atom-smashing in which high-velocity projectiles are used: in goes a neutron or deuteron on one side and out goes a proton or neutron on the other. But what if the impinging body is moving somewhat more slowly; will it not lack the kinetic energy to drive out another particle? If so, what happens then?

Referring again to the billiard balls in the hollow dish, let us imagine that the entering ball has only a little more than enough momentum to force its way in among the other balls. The excess kinetic energy is, of course, distributed among the other balls, but it is too slight to throw one of them out. As a result, there is too much mass inside the nucleus—and nature despises any excesses whatsoever. Nuclei in this condition are said to be *unstable*—that is, their internal stresses are all awry because of the presence of the extra neutron, which rocks the boat, as it were. The same unstable condition would exist if one neutron was *missing* from the nucleus. Nuclear instability is the hallmark of radioactivity! All the naturally radioactive elements are characterized by an excess of mass in their nuclei.

Nature has remarkable resources at her command. Physicians say that the accumulation and discharge of white blood corpuscles around a neglected sliver or other infected point is an effort of the bodily mechanism to expel the foreign material. The effort may be in vain, but if the source of infection is not otherwise removed, most serious results are likely to follow.

We have left an unstable nucleus hanging in thin air for a minute or two. Is anything happening to it, or have the original inhabitants resigned themselves to having a permanent guest? If we had spectrometers and other highly sensitive physical apparatus at hand, we should be

able to detect some emanation coming out of the nucleus, very similar to that from radium. We should also be able to identify this radiation, by passing it through a magnetic field, as consisting of gamma rays. The unbalanced nucleus is trying to restore its equilibrium by expelling the excess mass in the form of radiant energy. *A new radioactive substance has been born!*

It has been possible to measure rather exactly the kinetic energy of the emanations from these artificially radioactive nuclei. Without going into too many figures, the evaluations are from two to seven million electron volts for each nucleus so activated, which means that about .009 unit of mass has been transformed into energy.* The radiation keeps up until the excess mass in the nucleus has been dissipated. The time necessary to bring the nucleus back to normalcy varies greatly with the element; in some cases it is only a few seconds, in others a matter of months or even years. On the average, however, it is comparatively short.

Since the atoms of any substance can be made artificially radioactive at will by controlling the speed of neutron bombardment, the question has been raised as to whether atoms activated to an unbalanced state by the neutrons liberated from uranium in an atomic bomb will not give off large quantities of the lethal gamma rays for years afterward. It must be remembered that

*Libby, W. F., *Science,* Vol. 93, p. 283 (1941). Electrons also are given off.

these rays and free neutrons are among the most penetrating agencies known; to have either of them "on the loose" would bring death to hundreds or even thousands of people. As a precaution against this, England distributed and buried her radium supply (the whole gram of it!) during the war; if even this small quantity had been scattered to the four winds by a bomb, it would have gone on emanating gamma rays over a wide area for centuries.

This question of the permanence of the radioactivity induced in such earthy elements as calcium, silicon, and aluminum is hard to answer definitely at present. Tests made at the scene of the trial explosion in New Mexico showed that the sand in the immediate vicinity was still measureably radioactive after a lapse of nine weeks. The intensity of the radiation was so slight, however, that it could scarcely be called a menace to public safety.

56. Uses of Radioactive Isotopes

Naturally an atom which receives a neutron from external sources undergoes a temporary increase of one unit of mass; its atomic weight goes up a notch. It thus becomes an isotope, which we recall is an atom which is identical with all the other atoms of its kind except in respect to its weight. Many of these artificially radioactive isotopes are of such great value in

Press Assoc., Inc.

Figure 16. *Measuring radioactivity at site of test bomb explosion nine weeks later.*

medical and biochemical research that a brief digression may be justified.

The beneficial effects of gamma radiation on cancer are well known, the only drawback to the treatment being its terrific expense. It is doubtful whether more than a pound of pure radium exists in the purified state, and it is quite possible that there may be less than ten pounds of it in the entire earth. That fact gives some idea of the penetrating power of gamma rays! The

supply of other, less potent radioactive metals is not abundant. Therefore the possibility of being able to furnish medical science with gamma radiation on order was well worth exploring.

The name of Enrico Fermi will always be associated with induced radioctivity, as it was he who followed up significant experiments performed in France by Irene Curie and F. Joliot which had paved the way for Chadwick's discovery of the neutron. Fermi was the first to realize and test the possibilities of the neutron for bombarding nuclei, and to make atoms radioactive by this means. Since 1934 several such substances have been produced in quantity, especially phosphorus, which has been substituted for the scarce and costly radium in cancer therapy, thus adding one more beneficial technique to the battle with that still incurable disease. Considerable amounts of radioactive sodium and iodine have also been made.

It is often highly desirable in medical work to be able to trace the passage of certain substances through the body. This had never been possible before the introduction of radioactive isotopes. Suppose, for example, a physiologist wants to study the mechanism of iodine absorption in the body. He first feeds his experimental animals a little specially doctored iodine containing an unstable nucleus; then utilizing an ultrasensitive detector, such as Geiger-Müller counter, he can spot the location of the added

iodine in the organs by means of its gamma radiation, which is not of long enough duration to be harmful. Such artificially tagged substances are called "tracer elements", and they are sure to be one of the most useful tools of modern medical research. This is one by-product of nuclear disintegration which is of inestimable benefit to mankind.

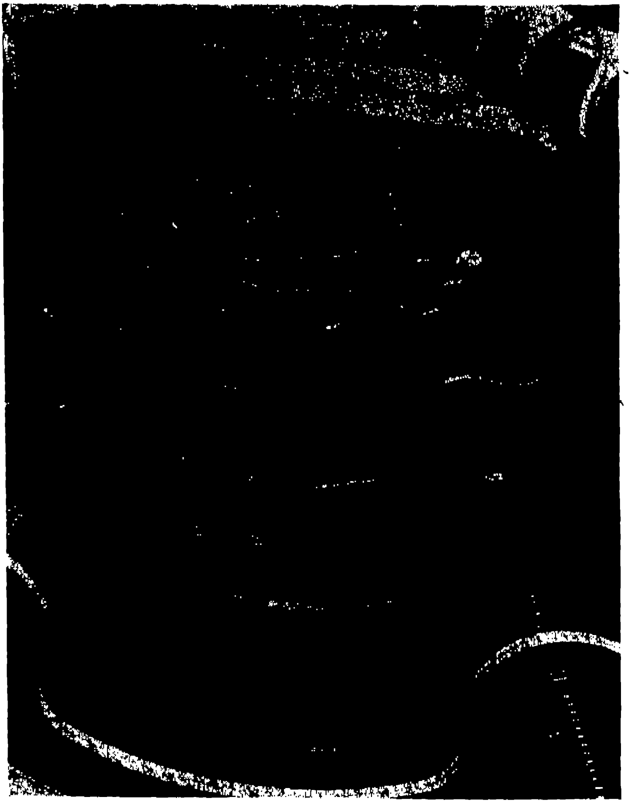
57. The Cyclotron

As yet no mention has been made of the man who has contributed more to nuclear disintegration technique than any other investigator—Ernest O. Lawrence, of the University of California. Lawrence had become interested in the possibility of obtaining energy from atoms when a National Research Fellow at Yale. In fact, he succeeded in measuring the energy necessary to tear an electron away from a mercury atom, thus determining exactly its "ionization potential", which he found to be about ten volts. Lawrence was a brilliant and resourceful young man, and he realized the tremendous energy necessary to give a projectile enough momentum to penetrate the powerful wall of electrical force which surrounds every atomic nucleus. It would require a current of millions of volts, far too high to be practicable. Then by chance he read an account of how a German scientist named Wideroe had accelerated atomic nuclei with a low-voltage arrangement, and this enabled him

to work out the essential principle of the cyclotron.

Before describing the cyclotron, some mention should be made of courageous and enterprising attempts to smash atoms by the use of high-voltage direct current. Following the example of Cockroft and Walton several scientific groups experimented with elaborate and impressive-looking installations like those illustrated. Foremost in this work was Robert Van de Graaff, of Massachusetts Institute of Technology, M. A. Tuve of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and scientists at the Westinghouse Electric and Manufacturing Co., of East Pittsburgh. These devices are called electrostatic generators; the principle on which they operate is simple theoretically, but extremely difficult to realize in practice, as gigantic equipment is necessary. The purpose is to impart a high velocity to a charged particle, such as a proton, by accumulating a tremendous voltage of positive electricity at one terminal, or electrode, and then discharging it through a vacuum. When a particle is accelerated in the vacuum by a charge of some six million volts, it should have enough kinetic energy to enter an atomic nucleus. Such generators found important use in developing the atomic bomb in New Mexico.

There is no need in this survey of the subject to elaborate the technical details of its construc-



World Wide Photo

Figure 17. *Assembling the porcelain insulating columns which support the giant electrode at top of the 65-foot atom-smasher at Westinghouse Research Laboratory.*

tion and operation. Lawrence's problem was to devise a means of speeding up positively charged atomic particles such as hydrogen nuclei or deuterons so that he could direct a stream of "bul-

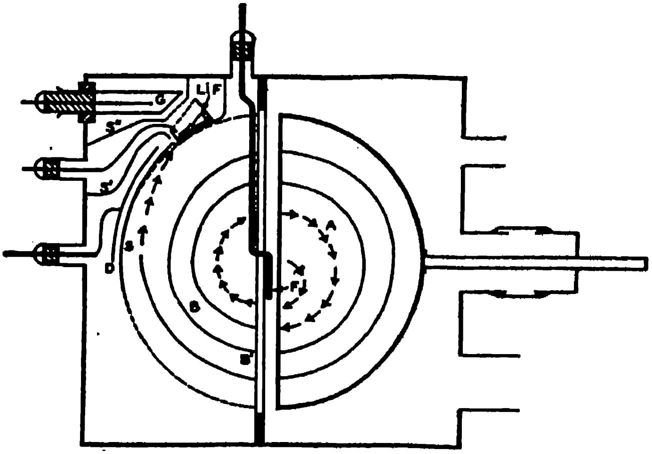
World Wide Photo

Figure 18. *M. A. Tuve adjusts some of the instruments in the Department of Terrestrial Magnetism at the Carnegie Institution of Washington. At top is positive terminal; vertically below is glass vacuum tube.*

lets" at the target nuclei at a much higher speed than had been attained by Cockroft and Walton: for the greater the mass of an atom, the stronger is the repulsion of its nucleus and the faster the projectiles have to move to penetrate it. Moreover, the acceleration must be brought about with a reasonably low input of electric current.

Lawrence hit on the idea of making his "bullets" traverse a low-voltage field many times instead of a high-voltage field once. He worked out his plan successfully on a small scale. For it he used a small horseshoe-shaped electromagnet with a circular vacuum pan between its poles. In the pan is obtained a supply of hydrogen nuclei, to be used as projectiles. Through the magnet runs a steady direct current, which creates a strong magnetic field in the pan. Then an alternating current of 2,000 volts is sent across the gap between the pole-pieces of the magnet. In response to this push, the nuclei in the pan begin to move in a circle, as charged bodies always do in a magnetic field. Just as they have completed a semi-circle, the alternating current reverses its direction, and the nuclei complete the circle with a fresh jab of 2,000 volts. This circular motion is continued, the nuclei receiving a new impetus at every half-circle; as a result they move farther and farther out toward the rim of the container. After they have received about a hundred impulses they are traveling at tremendous velocity; they are then released through an aperture and directed at the

target. The accompanying diagram shows the spiral course of the nuclei as they move through the vacuum pan, starting at point F.



From Darrow, "The Renaissance of Physics" (Macmillan)

Figure 19. *How protons or other nuclei whirl in a spiral in the cyclotron of Lawrence, receiving additional energy twice in every complete turn. (After M. Henderson)*

Lawrence's first cyclotron, as it was aptly named, was a limited success. The only trouble was that it was far too small to provide the acceleration Lawrence wanted. He built several more models in the William H. Crocker Radiation Laboratory at Berkeley, California, using larger and larger electromagnets and higher voltage, until finally he had a giant machine whose magnet alone weighed 220 tons. Its vacuum chamber is five feet in diameter, and it can accelerate deuterons (heavy hydrogen nuclei)

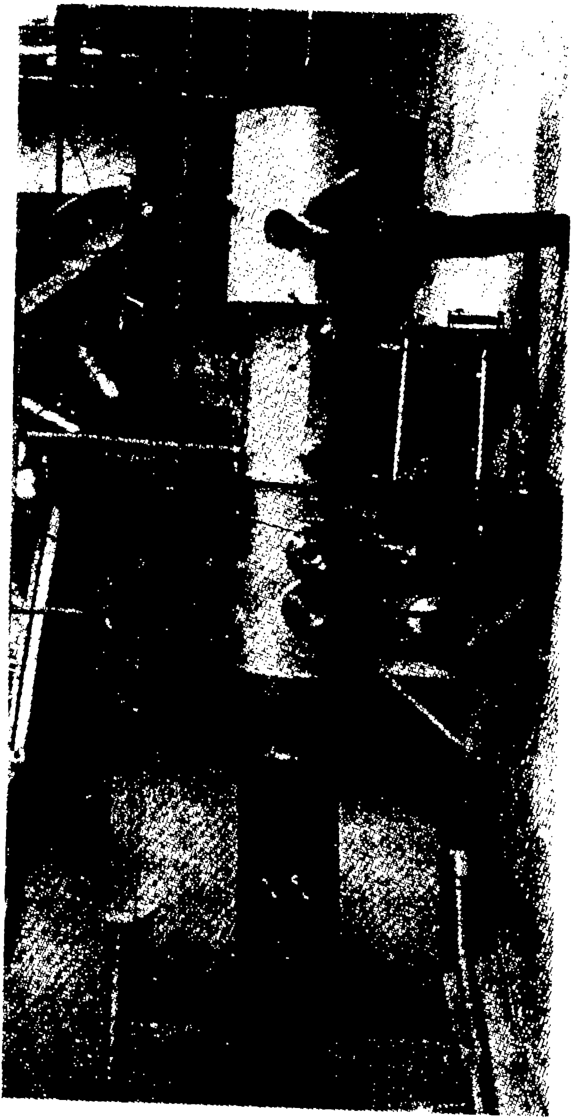


Figure 20. *The Cyclotron at the University of California.*

From Podolsky, "The War on Cancer" (Reinhold)

so that they have a kinetic energy of 16 million electron volts. As the beam is ejected into the air, it penetrates over five feet; the deuterons are moving at about 25,000 miles a second, and about 600 trillion of them come out every second —an energy equivalent to that which would be produced by thirty tons of pure radium if it existed! Directing this beam at a substance like beryllium results in a shower of neutrons. It may be that only one deuteron bullet in a hundred thousand hits a nucleus squarely enough to enter and drive out a neutron or proton, but many of them are captured by the nuclei of the target substance, which is thus rendered unstable. Over two hundred substances have been made artificially radioactive by use of the cyclotron.

It is essential for the operators to be screened behind lead baffles and tanks of water, which absorb the neutrons produced. These have a deleterious effect on blood corpuscles, and absorption of an abnormal quantity of them by the body through continued exposure to neutron-producing reactions is sure to cause death. Adequate protection is afforded by water barriers, which absorb the neutrons rapidly. Paraffin may also be used.

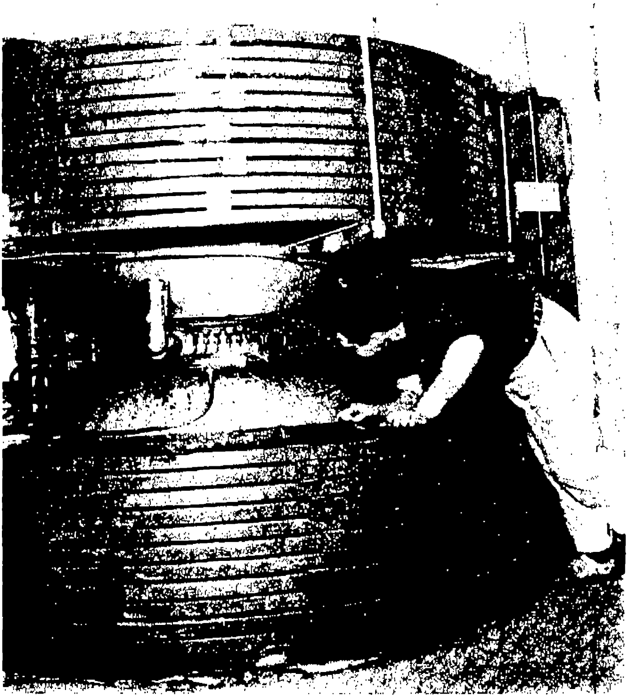
Lawrence did most of his early cyclotron work with deuterons, which were being produced in quantity by G. N. Lewis right there in Berkeley, where their existence had first been predicted. Harold C. Urey, who actually dis-

covered them at Columbia, was an alumnus of the University of California. As previously pointed out, these hydrogen nuclei of twice the normal mass are particularly effective because of their higher kinetic energy, although they are not as potent as the uncharged neutrons.

Lawrence also experimented with helium nuclei, which Rutherford had used in his epochal transmutation in 1919. With a power input of only 50,000 watts, Lawrence was able to project a beam of these nuclei having a kinetic energy of 32 million electron volts from his 220 ton machine before the war. He planned a much larger one weighing about 2,000 tons, work on which was interrupted by the war. Parts of it were used for important research work on the atomic bomb project.

Lawrence's success with the cyclotron led to its adoption all over the world. Rutherford installed one in the Cavendish Laboratory in England, L. A. DuBridge at the University of Rochester, K. T. Bainbridge at Harvard, and Robley Evans at Massachusetts Institute of Technology, to mention only a few. The Westinghouse Electrical and Mfg. Co. is the only commercial institution in the United States to possess a cyclotron. In 1940, there were at least forty in operation throughout the world, including those in use in Germany and Japan.

Valuable as it is in biological, medical and metallurgical work, and in providing a means of learning more about atomic structure and the



World Wide Photo

Figure 21. *Inside the University of Michigan cyclotron. Top and bottom large structures are magnetic coil windings. Between pole pieces is the vacuum pan.*

nature of that enigma of science—energy—the cyclotron is not necessary for splitting the uranium nucleus; indeed this is the exception rather than the rule. The stage is pretty well set now for a look at the specific subject of this book—for up to this point we have not seen a nucleus split, although a few million have been slightly damaged!

58. *Uranium*

URANIUM WAS NAMED after the planet Uranus, which was at that time thought to be the outermost planet of the solar system, corresponding to uranium's place in the Periodic Table. It is one of the rarest metals known, and occurs in pitchblende, a composite ore found in Central Europe, and recently discovered in the Great Bear Lake region of northern Canada; radium is also obtained from this ore. Uranium is sometimes associated with vanadium ore, called carnotite, as in the Utah deposits. It is extremely difficult to extract and purify—so difficult that before 1940 no more than a few pounds of it existed even in the impure state. Until the artificial creation of two new elements of still higher atomic weight, which will be described presently, uranium was the heaviest and most complicated atom known. Its nucleus contains 92 protons and 146 neutrons, traveling around which are 92 planetary electrons in numerous orbits. It occupies the last position in the Periodic Table, with an atomic weight of 238, and contains three isotopes. The one in which we are most interested, U-235, occurs in the ratio of one to 140; that is, for every 140 atoms of the normal form, there is one atom of the 235 isotope which, being highly unbalanced, is intensely radioactive. There is another isotope, U-234, whose nucleus lacks four protons; but as this is about 100 times as rare as U-235, it is of no practical use.

The extreme scarcity of uranium should be emphasized. Figures obtained in 1940 showed that, with the concentration and purification techniques then known, it would take 75,000 years to make a pound of highly purified uranium, and well over a million years to isolate the same quantity of the rare U-235 isotope.* A microscopic amount of U-235 was produced in the General Electric Laboratories by vaporizing uranium ore in a small electric furnace and then sorting the isotopes with the mass spectrograph as they were separated by traversing a magnetic field. A far more rapid process was being worked out in Sweden when the war intervened. The prospects for harnessing atomic power in the near future did not look very bright!

59. Uranium Fission

IN 1934 ENRICO FERMI, then in Italy, had investigated the possibility of splitting the heavy uranium nucleus with neutrons. He reasoned that the terrific positive electrical charge of +92 on the nucleus would be impossible to penetrate with any but a neutral particle, which would be immune to electrical repulsion. Fermi was fortunate in having neutrons at hand, as they had been discovered only two years before. He did considerable experimenting, and succeeded in creating the artificial isotope U-239, by bombarding U-238 with neutrons.

***Time*, May 27, 1940, p. 46.

It was not till January 1939 that the first actual splitting was reported by Otto Hahn and his colleagues, Liese Meitner and O. R. Frisch, of the Kaiser Wilhelm Institute at Berlin. As this was only nine months before Hitler's invasion of Poland, it is no wonder that Allied

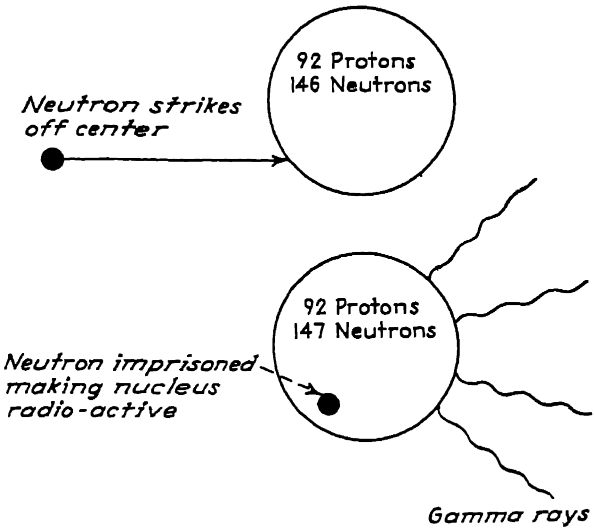


Figure 22. *Neutron capture by U-238 nucleus, resulting in the artificial radioactive isotope, U-239, first produced by Fermi.*

scientists were apprehensive that the Germans might develop an atomic bomb! Hahn is said* to have achieved his result by using neutrons obtained by bombarding a beryllium target with alpha particles obtained from radon, which seems altogether reasonable, as beryllium is an

**Time,* Feb. 6, 1939, p. 21.

excellent source of neutrons. He produced an explosion on an atomic scale, which probably involved no more than a few nuclei; he calculated the energy release as 200 million electron volts per nucleus. He also reported the presence of one atom of an isotope of barium for every atom of uranium split. It was later found that an atom of krypton is also formed, and that sometimes still other pairs of elements result.

As a result of this pioneer experiment, leading physicists in Europe and America at once began investigating its practical application. Niels Bohr, J. A. Wheeler, Enrico Fermi, and others discussed the possibilities widely both among themselves and in scientific journals. Borrowing a term from the biologists, they assigned the word "fission" to the crack-up of the uranium nucleus and the subsequent formation of by-product elements (which by the way are not to be confused with the two artificially made new elements, neptunium and plutonium). Fission is an elegant word for "splitting"; it is what happens to an amoeba or other single-celled organism when it desires to reproduce itself—it simply divides in half.

60. Neutron Production

AS A RESULT of these discussions the idea occurred to Fermi that neutrons might be produced during the fission process. Let us see why

he suspected this. Hahn's experiment had indicated that the nucleus of U-238 did not divide in exact halves containing 119 units of mass each, but rather into sections having 140 and 90 units of mass apiece. Hahn, with the inspired assistance of Liese Meitner, had identified the heavier one as an isotope of barium, the normal atomic weight of which is 137. Regardless of whether the isotope weighed one unit more or less than the normal weight of 137, Fermi saw that if the portion of the U-238 nucleus having a mass of 140 was really barium—and there was no reason to doubt it—there must be an excess of neutrons which are ejected during fission. This was a most significant point, for might it not be that these two or three *surplus neutrons* would then proceed to rupture the next nucleus, and so on, thus causing a continually reduplicated, or chain reaction?

Meanwhile, Hahn's original experiment had been confirmed both in the United States and Europe. After a year had passed several additional facts had come to light. To get a clear picture of what was known about the subject at the end of 1940, it might be well to summarize the facts which were of crucial importance for the future development of the atomic bomb, which will always be regarded as the No. 1 achievement of American science and industry working together.

61. Fission Fragments

WHEN A NUCLEUS of either U-238 or U-235 is split by the impact of a neutron, two atoms of other elements are formed. These are elements which are located somewhere near the center of the Periodic System, and are usually isotopes which are temporarily unstable, and therefore radioactive. For example, the fission of a U-238 nucleus may produce one atom of barium and one of krypton; no less than thirty different elements have been identified in the course of recent experiments. The kind of elements formed depends on how the uranium atom divides. As might be expected of bodies accelerated by 200 million electron volts, these atoms have tremendous kinetic energy, and *it is this which provides the blast effect or demolition force of the atomic bomb.* The energy released by fission is analogous to that produced by the explosion of powder in the minuteman's musket, or in the breach block of a 16-inch gun; the atomic fission products represent the bullets or the shells propelled by the explosion (except, of course, that shells carry their own demolition charge with them). Basically, the atomic bomb's destruction is caused by the kinetic energy delivered by small particles moving at terrific speeds, just as is the case with ordinary explosive bombs; the great difference lies in the source and quantity of the energy.

62. Neutron Capture

Uranium fisson produces from one to three neutrons per nucleus, in addition to the atomic fragments. These neutrons originally existed in the uranium nucleus and their liberation is of the utmost importance, for without these newly released neutrons there would be no possibility of the chain reaction that makes atomic power for practical purposes a reality. We shall have a good deal more to say about neutron production presently. At this point, however, it is desirable to call attention again to the importance of the ability of a nucleus to "capture" neutrons. By "capture" we mean that the nucleus—U-238, for example—admits the impinging neutron *without splitting*—in other words it becomes unstable and radioactive, as was described in detail in an earlier section.

Now when this happens, the neutron so captured is lost, as far as its further chance to cause fission is concerned. It has literally been seized and imprisoned by the target nucleus. When U-238 is bombarded with neutrons, the object is to cause as high a percentage of fissions as possible; but it can readily be seen that such a vast proportion of the bombarding neutrons will be captured that there are only a few left to score the direct hit on the nucleus which is necessary for fission to occur.

The U-238 nucleus is far more likely to capture a high percentage of neutrons than is the

U-235 isotope; or to put it another way, the chances for a large number of fissions is much greater with U-235. The reason for this is that the so-called "capture cross-section" of U-238 is considerably larger than that of U-235, and it consequently has a much greater chance to absorb neutrons without splitting. A crude but

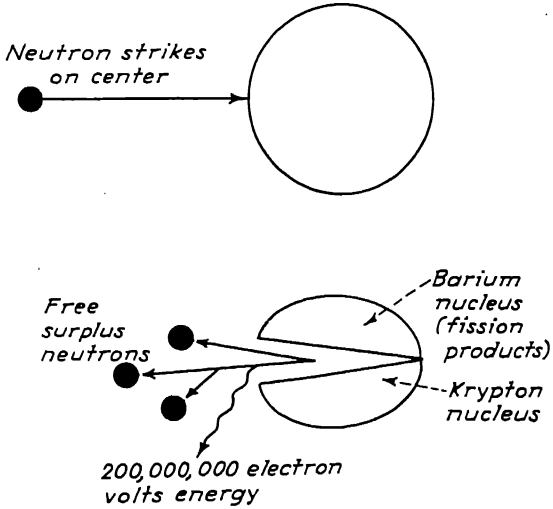


Figure 23. *Fission of uranium nucleus by a neutron.*

fairly good idea of what is meant by capture cross-section may be given by likening these nuclei to two baseball players. Let us say that U-238 is a shortstop and U-235 a second baseman. The shortstop's reach with his arms extended we may imagine to be five feet, if he is tall and rangy; the second baseman's reach, however, is only four and a half feet. He there-

fore has a "capture cross-section" 10 per cent less than that of the shortstop. In like manner U-235 has a smaller capture cross-section than U-238.

Moreover, the extent to which these uranium isotopes capture neutrons depends greatly on the *speed* of the neutrons. Those which move at the normally accelerated rates which we have been discussing so far are called *fast* neutrons. Both U-238 and U-235 nuclei can be split by these, but because of the tiny proportion of U-235 in uranium, it is highly unlikely that these will be struck. To insure a greater percentage of neutron hits on U-235, means have been devised to retard the impinging neutrons to such an extent that they will not affect U-238 at all, and thus will be free to split U-235.

63. The Problem

Such was the status of the knowledge of atomic power when, 18 months after Hahn reported the first successful fission of a uranium nucleus, the government called upon the technical personnel of the United States to find ways and means of releasing and controlling this perfectly terrific amount of energy on a large scale. All the experimentation up to that time had been carried out with microscopically small amounts of uranium. No one knew exactly what difficulties lay ahead, except that they would be enormous. There was virtually no pure uranium

trophe hovering in the offing is not exactly a nerve sedative.

A brief survey of how the problem was met and solved will be of interest. Because of the limitations of space and time, only the essential outlines can be given. But no one can read Professor Smyth's report* without a thrill of admiration for this magnificent technical and administrative accomplishment.

64. Probabilities

SUPPOSE WE START with a lump of purified uranium, at which we direct a beam of neutrons from a suitable source such as beryllium. What are the probabilities involved? First of all, it must be borne in mind that the ore contains 140 times as much U-238 isotope as U-235, and that the latter is less likely to be affected by rapidly moving neutrons because its "capture cross-section" is smaller. Here are the neutrons traveling toward the target sample containing billions of atoms of U-238 and several million atoms of U-235.

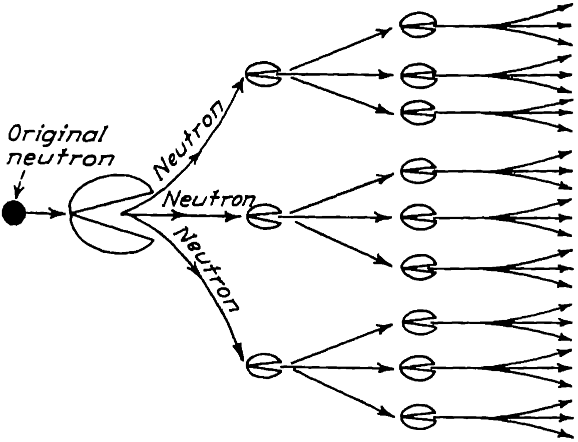
There are four possible ways in which the neutrons may be consumed: (1) they may escape the target altogether; (2) they may be captured by the nuclei of extraneous substances

*"A General Account of the Development of Methods of Using Atomic Energy for Military Purposes under the Auspices of the U. S. Government," by H. D. Smyth, Chairman of the Dept. of Physics, Princeton University; published in book form by Princeton Univ. Press, Sept., 1945.

:d impurities; (3) they may be captured by 38 nuclei by the millions *without* splitting 1; or (4) they may strike a U-238 or U-235 eus on the nose and create a fission. How-, in the relatively few cases in which fission .rs, most of the new neutrons thus produced immediately be devoured by U-238 nuclei, :h have a large "capture cross-section"; pos- ʳ a few of them will cause fissions, but the ›ability is strongly against more than two ıree successive fissions taking place in U-238 result of the original one caused by the im-'ing neutron. Even if by chance a fast neu- split one of the rare U-235 atoms, the same g would occur: the neutrons produced ld all be captured by the vastly more numer- 1eavy nuclei.

ι other words, U-238 can be split with a fair 'ee of regularity *as long as an external sup-)f neutrons is fed into it*. But if this supply ıt off, the reaction will not be self-propa- ıg, because the creation of new neutrons by ɔns will be much *less* than the combined con- ɔtion due to escape, losses to impurities, and ure without fission. The crux of the problem 'eating a chain reaction—which is the only : of controlled use of atomic power, whether ɔmbs or for peaceful purposes—is to main- a system such that the production of neu- s by fission is continuously greater than

A value known as "multiplication factor *k*" was determined as the ratio of the number of new neutrons produced by fission to the number originally present in the system. The entire success of the atomic bomb project hung upon whether or not this ratio could be kept greater than 1.00. If it could, it would mean that an excess of freshly formed neutrons was always on



Figue 24. *Chain reaction. Up to this point 13 fissions have occurred, releasing a total of 2,600,000,000 electron volts of energy. The chain reaction continues till all nuclei present are split, each fission liberating three fast neutrons.*

hand to create new fissions; if on the other hand the U-238 and the impurities soaked up the neutrons as fast as they were formed, no chain reaction could ever be possible.

It seemed obvious from the outset that there was no hope of attaining the goal with neutrons moving at rapid speeds, because the U-238

would capture such a large proportion of them without splitting, and would also eat up the new neutrons formed by the few fissions that did occur. In a word, the mathematical probabilities of the situation were all against success as long as fast neutrons were used.

65. *Slow Neutrons and Moderators*

Now suppose by passing the neutrons through a retarding substance, known as a *moderator*, they are made to move so slowly that by the time they reach the nuclei of U-238 they are unable to force their way into them. They will therefore have plenty of opportunity to strike and split one of the few U-235 nuclei. The effect of this artificial slowing down of the neutrons is to remove almost completely the possibility that they will be lost by U-238 capture—simply because they have too little kinetic energy to penetrate the heavier nucleus. Some loss, though considerably less than before, is due to escape from the system and to capture by impurities; but the net result is a far higher probability that a chain reaction will get under way. The rate of capture of new neutrons by U-238 and fission products may eventually overtake the release of neutrons by U-235 fissions and the chain reaction will stop. However, the fission-produced neutrons may in turn be so retarded by the moderator substance—usually graphite—that they will themselves become slow neutrons.

An essential factor in atomic energy release is the speed with which the reactions occur. The whole point of the large-scale trials to be described later was to see whether or not controlled chain-reactions were possible. Suppressing the high rate of neutron capture by using slow neutrons seemed to be the only way of tapping the rich vein of energy in the U-235.

66. Purity of Materials

EVEN THOUGH THE capture cross-section of U-238 is greater than that of U-235, it is not nearly as large as that of other elements, including those resulting from fission. For this reason, the impurity factor in large-scale atom-smashing created a tremendous obstacle. Any element other than uranium must be considered an impurity. Therefore it was clearly impossible to obtain a chain reaction unless both the uranium itself and the graphite moderator were purified to such an extent that they contained only a few parts per million of foreign substances. This may not seem like much of a problem to the untrained observer, but it was as hard a one to surmount as any. Before 1940 less than a pound of pure uranium had been made in the United States, and no graphite even approaching the required standard of purity had ever been produced. Pure beryllium also was essential as a neutron source; this too was unavailable, and there were no facilities at hand to make it. All

these discouraging drawbacks faced the technicians in charge of the project in 1941.

The uranium supply problem was solved by development of an ether extraction process at the National Bureau of Standards, which removed virtually all the impurities. It was taken over by the Mallinckrodt Chemical Co., and soon deliveries of uranium dioxide of suitable purity were available. But this was not pure uranium metal—it still had to be "reduced". The Westinghouse Electric & Mfg. Co. had produced about half a pound of it by a slow process of their own which made the metal cost about $1,000 a pound. A quicker reduction process was found which required the use of uranium tetrafluoride. With the cooperation of the Du Pont Co., The Union Carbide and Carbon Corp., and the Harshaw Chemical Co., this problem was also solved, and a sufficient supply of highly purified uranium metal was assured. This was being produced by Westinghouse at the rate of 500 pounds a day by early 1943, at a cost of only $22 a pound.

By equally fast and intelligent cooperation, ways were found to produce highly purified graphite. Both the National Carbon Co. and the Speer Carbon Co. were responsible for this important contribution to the project.

67. Pure U-235

THE WHOLE POINT of using a highly purified graphite moderator is to retard the neutrons to

such an extent that they will not be captured by either U-238 or extraneous substances, and will thus be able to cause fission in the sparsely scattered atoms of U-235. Now U-235 is susceptible to either fast or slow neutrons; but when the latter are used, the probability of a *rapid* chain reaction is slight because, as just pointed out, a great number of the fast neutrons released by fission will at once be captured by the U-238 nuclei; whether they are or not depends wholly on the fortuitous position of the U-238 in the system—that is, on how far the fission-produced neutrons travel through the retarding medium, or moderator, before striking them. Fission induced by slow neutrons is a possible source of a slow, steady energy production, such as would be desirable for electric power; but nothing less than a *rapid* and unimpeded chain reaction will do for a bomb. This is obtainable by the use of fast neutrons on highly concentrated U-235. Here was perhaps the greatest single obstacle to the success of the project, for no method of producing pure U-235 in the necessary quantities was known.

It is true that there is a certain amount of fast-neutron capture even by U-235, but it is not sufficient to inhibit a chain reaction. Moreover—and of great practical significance—with pure U-235 the need for a moderator would disappear, as there would be no necessity for retarding the neutrons at all. The moderator is

only a device to eliminate the blanketing effect of U-238. Once the U-235 is unencumbered by the neutron-capturing proclivities of its heavy isotope, the coast is clear for extremely rapid chain fission.

Since even pure uranium contains only 1 atom of U-235 to every 140 of U-238, it was imperative that some means of separating out the light isotope be developed. We have already mentioned some earlier attempts to do this; when the atomic bomb investigation got under way in 1941, the only separation methods known would have taken thousands of years to produce enough U-235 for one bomb! We shall presently see how this staggering obstacle was overcome: it was one of the two main lines of investigation and development in the history of the Manhattan District, as the atomic bomb project was officially termed.

68. The New Elements

It is impossible to present the story of this gigantic program in chronological sequence, because all its important phases were being worked out simultaneously. The attempt will be, therefore, first to establish the basic factors and discuss their solutions in a general way, reserving a brief account of the plant installations till later. It must be remembered that "time was of the essence"—a statement which it is indeed a pleasure to put in the past tense!—and that

much of the information given above had been obtained by 1942 from the operation of uranium-graphite lattice piles at Columbia University and under Stagg Field at the University of Chicago: for example, the discovery of the impossibility of obtaining a sufficiently rapid chain reaction from unseparated isotopes and of the existence of a wholly new chain-reactive element. In this resumé the theories developed from these installations are discussed before the details of the plants themselves.

The necessity for large-scale separation of U-235 from U-238 had been established as one of the two great problems. In the early months of the investigation, this appeared to be the only really crucial requirement of an atomic bomb. But experimentation with uranium-graphite piles soon turned up a possibility that had not been seriously considered at first, although the phenomenon had been discovered by Fermi at Columbia several years before. This was the fact that when an atom of U-238 captures a fast neutron it not only becomes radioactive U-239, as one would naturally suppose, but after a while may be transformed into *a new element* of atomic number 93; this in turn adds a unit to its nuclear charge and becomes still another new element which is an excellent chain reactor. Perhaps we had better slow this down a bit and try to visualize what happens.

When U-238 is continuously bombarded by neutrons, those which do not cause fission re-

main in the nuclei. Each nucleus can thus capture one neutron, and in so doing it becomes a U-239 nucleus:

$$_{92}U^{238} \quad + \quad _{0}n^{1} \quad \rightarrow \quad _{92}U^{239}$$

Now a neutron, we recall, is a combination of a proton (+) and an electron (—). Apparently after the captured neutron has joggled around awhile (23 minutes, to be exact) in the U-239 nucleus, it splits up into a proton and an electron. The nucleus thus adds one unit of charge (proton) to its mass, and the electron (e) is then radiated off. This accounts for the formation of a new element called neptunium,* with an atomic weight of 239 and atomic number 93:

$$_{92}U^{239} \quad \xrightarrow[\text{23 minutes}]{} \quad _{93}Np^{239} \quad + \quad _{-1}e^{0}$$

This nascent element doesn't seem to like the world it has just entered; so after a couple of days one of its original neutrons divides into proton and electron, thus adding another positive charge to the atom, which is now called plutonium.* The electron is given off as before:

$$_{93}Np^{239} \quad \xrightarrow[\text{2.3 days}]{} \quad _{94}Pu^{239} \quad + \quad _{-1}e^{0}$$

Plutonium is quite stable, but eventually turns back into U-235. It is highly chain re-active.

The great practical significance of this series

*These names were assigned to correspond to the positions of the three outermost planets in the solar system: Uranus, Neptune and Pluto. Neptunium and plutonium presumably occupy the next locations beyond uranium in the Periodic Table.

of transformations was that U-238 could be used as a source of U-239 *without* separation of isotopes; thus a given amount of uranium metal would produce 100 times as much atomic energy as previously supposed. Chemical separation of plutonium from U-238 was necessary, however. Plutonium can be used directly as a chain fission

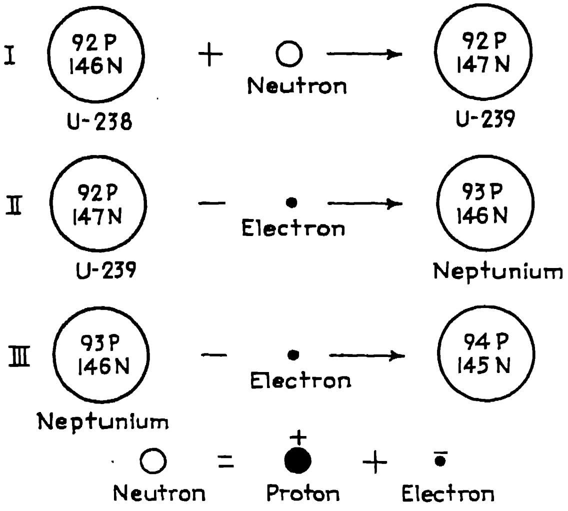


Figure 25. *How U-238 becomes Plutonium.*

producer, and has some technical advantages over U-235, chief of which is that its rate of neutron capture is much less—in other words it gives a higher proportion of fissions and therefore a still more effective chain reaction.

It is now obvious why these two prime objectives were carried along simultaneously. The discovery of the possibilities of plutonium re-

sulting from intensive work with Lawrence's cyclotron at Berkeley, California, came at the same time that the original plans for developing pure U-235 were being made. Consequently plutonium production in quantity was undertaken, and it became a contest as to which would give quickest and best results. This is the meaning of the announcement that the second atomic bomb dropped on Japan rendered the first one obsolete. The first contained U-235, the second its more potent rival, plutonium.

69. Chemical Separation of Plutonium

One of the reasons why it was felt that plutonium was the more desirable of the two was the extreme difficulty of preparing usable quantities of U-235 by physically separating it from U-238. This process is extremely slow and tremendously complicated from the engineering standpoint, but the separation of plutonium from uranium can be performed by *chemical* means. With a sample of plutonium weighing only 500 micrograms—less than enough to make an ordinary pinhead—obtained by cyclotron bombardment at the University of California and at Washington University in St. Louis, microchemical separation experiments were conducted by the staff of the Metallurgical Laboratory of the University of Chicago, headed by A. H. Compton. Their conclusion was that chemical separation is entirely feasible; indeed

several methods of extracting it from a neutron-bombarded mass of uranium were evolved. This discovery was a splendid contribution to the ultimate success of plutonium production and the Metallurgical Laboratory deserves great credit for its accomplishment.

The intricacy of this problem can be appreciated only when one realizes that several other radioactive substances are present in the material containing plutonium. For one thing, the fission products of the U-238 atoms which are incidentally formed may comprise a score or more of highly unstable elements which are giving off gamma rays and electrons, and though some of them achieve stability in a minute or two, others continue to be radioactive for weeks. In addition to these, intermediate radioactive substances are formed, such as U-239 and neptunium; the latter, however, turns promptly into plutonium.

It was necessary to provide equipment for separating each day several grams of plutonium from 18 or 20 pounds of uranium containing a high percentage of dangerously radioactive substances—and the plutonium had to be in an extremely pure condition. As the details of chemical separation processes make dull reading, we shall merely note here that the precipitation method was selected* as the most efficient, and this was developed to a point where it was ready

*Three other methods were found possible: evaporation, absorption, and solvent extraction.

for installation by the time the plutonium plant was operating at Hanford, Washington. It is interesting to realize that the selection of this method was based on the knowledge of plutonium gained from the minute quantity produced in the cyclotron—about half a milligram!

70. U-235 vs Plutonium

BEFORE GOING ON to describe the methods used to produce pure U-235, let us review briefly the status of the atomic energy problem up to this point. Here are the salient facts mentioned in the preceding sections.

(1) It had been found possible to create and maintain a chain reaction in purified uranium by retarding the neutrons with graphite. The fission-produced fast neutrons were numerous enough to slightly exceed the rate of capture by U-238 and impurities and loss by escape from the system.

(2) It had been foreseen that this reaction would not be sufficiently rapid for military purposes; it was therefore essential to obtain U-235 in the pure state by physically removing it from U-238. With U-235, fast neutrons could be used, eliminating the need for a graphite moderator.

(3) The practicability of producing a new element, plutonium, with the same set-up as used for slow chain reactions was established, although none had as yet been made in this way.

(4) This element is formed by fast-neutron capture by U-238: it is more highly chain-reactive than pure U-235 and can be chemically separated from U-238.

(5) Plutonium production appeared to be even more desirable than that of U-235.

71. Separation of Uranium Isotopes

THE ENTIRE POSSIBILITY of separating the extremely rare isotopes from the main body of an element depends upon the difference in the masses of their atoms. Deuterium, the isotope of hydrogen, is not a typical example of this difference because it is the only isotope whose mass is twice that of the normal element. In all other cases the mass discrepancy is comparatively small; in oxygen, for instance, the atomic weight of the regular form is 16, and of its isotopes 17 and 18 respectively. Even this is large on a percentage basis compared with uranium, where the light isotope is only three units less in atomic weight than the heavy one, based on a total of 238. Nor only is there a difference in quantity of 140 to 1, but a difference in mass of only a little over 1 per cent! To remove the lighter from the heavier obviously is a task for only the most highly sensitive processes, which even if successful could produce only very small quantities of U-235.

In early 1940, A. O. Nier, of the University of Minnesota, had isolated a tiny speck of U-235

by means of the mass spectrograph. This is an excellent method in some ways, but it requires an unthinkable amount of time. The problem was turned over to a group of scientists at Columbia, among whom was Harold C. Urey, of heavy water fame. At this time seven methods of small-scale separation were known, all based on the slight difference in mass between U-238 and U-235. Of these, three will be discussed.

The only hope of carrying out a separation of two substances as nearly alike as these is to handle them in such a condition that the atoms can pass one another with a minimum amount of interference. Since the atoms in a gas move much more freely than those in a solid or liquid, it is not surprising that the three physical separation methods referred to have one factor in common: the uranium must be in the form of a *gaseous* compound. This compound is called uranium hexafluoride, and the two isotopic forms are $U^{238}F_6$ and $U^{235}F_6$.

Each of the three methods is quite simple in theory—and from the engineering standpoint, almost hopelessly difficult to carry out on a large scale. Indeed, the chief purpose of describing them in some detail is to give an idea of the almost insuperable obstacles confronting the technicians of the Manhattan District project. Aside from this, however, they are interesting in themselves, and the manner in which they

were solved adds to one's respect for the genius of American scientists and engineers for doing the impossible.

72. *The Gaseous Diffusion Method*

HAVING OBTAINED A quantity of uranium hexafluoride gas, how would one start to segregate the few molecules of $U^{235}F_6$ from the 140 times greater number of $U^{238}F_6$? It was mentioned in the early discussion of gases that, since the molecules of all gases have the same average kinetic energy, it follows that molecules of the *lighter* gases must move faster than those of the heavier. It is on this fact that the gaseous diffusion process depends.

Suppose that we have a barrier riddled with holes, each of which is just large enough to allow a molecule of uranium hexafluoride to squeeze through. On one side of this barrier we place a chamber containing the gas to be separated, at normal atmospheric pressure of 15 pounds per square inch. On the other side we have another chamber pumped down to a vacuum of about one-tenth of this pressure—say one to two pounds per square inch. What will happen? Impelled by the pressure difference on the two sides of the porous barrier, all the molecules of the gas will move toward it; but the $U^{235}F_6$ molecules, being a trifle *lighter,* will move a trifle *faster*. Theoretically, these reach and pass through the barrier first; but in prac-

tice, so many $U^{238}F_6$ molecules also get through that after a moment or two the two gases are almost in the same condition as they started; thus the "straining" or diffusion process has to be repeated over and over again before the lighter molecules are separated in the necessary concentration.* The longer each diffusion is allowed to go on, the more heavy atoms pass the barrier and adulterate the small amount of 235-rich gas on the opposite side. Since there is no way of preventing this because of the extremely small difference in mass of the two molecules, the only way of ever obtaining relatively pure $U^{235}F_6$ is to return about half the diffused gas to the other side of the barrier and let it strain through again to remove a few more molecules of $U^{238}F_6$; the other half is passed through another barrier to the next stage.

The process is reminiscent of the endless story of the ants crawling single-file into the emperor's barn, each ant carrying off a single grain of wheat! Preliminary calculations showed that the amount of U-235 obtained pure at one pass would be negligible; the only way to get results would be to keep on "recycling" and passing new barriers until a total of *four thou-*

*Assuming that the diffusion rate of two gases through a porous barrier is inversely proportional to the square root of their molecular weights, the ideal separation factor for this problem is given by $\sqrt{\frac{M_1}{M_2}}$ where M_2 is the molecular weight of $U^{238}F_6$ and M_1, that of $U^{235}F_6$.

sand separate diffusions had been made! This would mean that about 100,000 times the volume of gas finally obtained would have to be put through the first barrier!

73. *A Production Nightmare*

Since each diffusion required a new chamber, or "stage", into which the U-235-rich gas must be passed, it was evident that, in order to obtain a few grams of fairly pure U-235 a day, over 4,000 chambers would have to be constructed, each pair being separated by a porous barrier. Moreover, each time the gases were put through a stage they would have to be pumped back to the original pressure differential before recycling and delivery to the next stage. This required an intricate and extensive system of pumps, and detailed study of the most efficient types. Another difficulty was that the uranium hexafluoride gas is a difficult one to use, as it is a solid at normal temperatures and pressures. The possibility of finding some other gaseous compound of uranium was investigated, but no mention is made in Professor Smyth's report as to whether or not this search was successful.

All of these obstacles were known before the decision was made in 1942 to proceed with the installation of a gaseous diffusion separation plant; it was at about this time also that plutonium production was definitely agreed upon. The first great problem was that of obtaining a

non-corrosive porous barrier material in sufficient quantity. To be effective, such a barrier must be perforated with billions of holes no larger than one-millionth of an inch in diameter! For a series, or "cascade", of 4,000 stages, computations showed that acres of barriers would be necessary. Let no one suppose that holes of this size could ever be drilled by mechanical means; the report is silent on the method used, though it would be interesting to know. Various types of barriers were tried, combining the ideas of many men; improvements were steadily made, until finally in 1945 a really satisfactory one was found, which could be manufactured in large quantities. From the essential specifications just mentioned, it can well be imagined that a great deal of ingenious thought went into the solution of this phase of the problem. The M. W. Kellogg Co. was assigned the responsibility for planning the large-scale installation; for this purpose a special subsidiary called the Kellex Corporation was formed, under the direction of P. C. Keith. This organization also carried out much of the research and development work.

In addition to the barrier problem there was the important matter of pumps. No type of pump in service in 1941 was exactly right, and considerable experimentation was necessary to obtain accurate specifications. The tremendous number of pumps required to operate the 4,000-stage cascade, and the fact that they must be

leak- and corrosion-proof and must operate at less than atmospheric pressure complicated the situation. New types of vacuum seals and other technical improvements also had to be developed.

The plant was finally installed at Clinton, Tennessee, the construction work being done by the J. A. Jones Construction Co., Inc., of Charlotte, North Carolina. It was put into operation a few stages at a time and is now performing consistently under the supervision of the Carbide and Carbon Chemicals Corporation. Its capacity may be estimated at about two pounds of U-235 a day—about half enough for one bomb. Not all the details as to how these apparently insuperable production obstacles were overcome have been released; but it can be said—and is indeed obvious from the foregoing bird's-eye view of the problem—that this was one of the most difficult and most ably handled development achievements of the entire atomic bomb project.

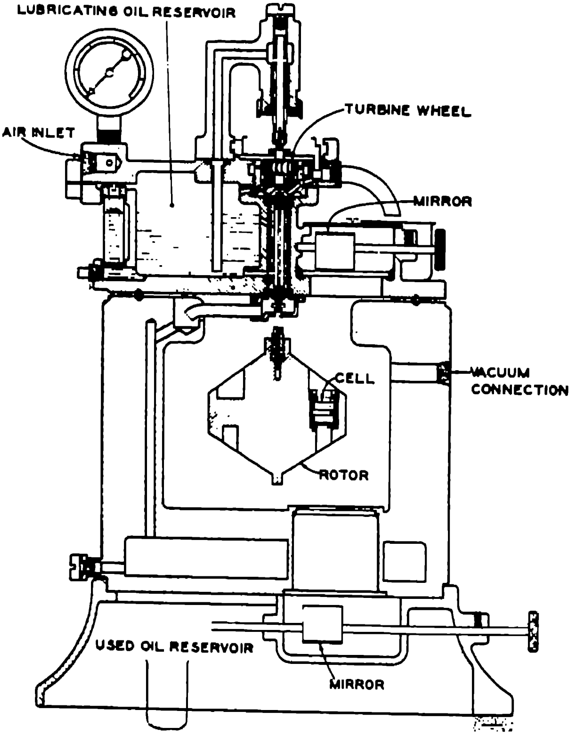
74. *Centrifugal Separation*

THE SEPARATION OF uranium isotopes by whirling them in a high-speed centrifuge was given a great deal of thought, and extensive small-scale trials were made. Though this method was eventually discarded, it was seriously considered for some time; we describe it here not only because of its mechanical interest, but because it indicates the amount of parallel investigation

that was carried on. Time was such a critical factor, and the project had so many ramifications, that all phases of it had to be studied concurrently; in many cases where several ways of accomplishing a given result were theoretically possible, all had to be evolved simultaneously, as insurance against failure of the others. This was true of the minor as well as the major aspects of the project. That so much noteworthy progress was made along so many lines at once is even more astonishing than the final successful outcome of the techniques actually put into production.

The principle of centrifugal separation is even simpler than that of gaseous diffusion. If you placed some peas and some marbles in a metal container and revolved it fairly rapidly for a few moments, you would expect that, on opening it, you would find the marbles distributed around the circumference of the container and the peas collected at or near the center. The effect of the centrifugal force of whirling is to throw the heavier particles to the outside, and keep the lighter ones close to the pivotal point. This principle is applied in industry when it is desired to separate solids from liquids of about the same specific gravity. The best illustration of this is the concentration of rubber latex. In its natural state latex is about two-thirds water and one-third rubber particles. Since the latter are only slightly lighter than water, the most effective way of obtaining a latex "cream" which

will contain about 60 per cent rubber particles is to place the latex in a centrifugal separator. As it revolves rapidly, the water is thrown outward while the particles remain concentrated near the center.



From Alexander, "Colloid Chemistry," Vol. 6 (Reinhold)

Figure 26. *Sharples suspended air-driven ultra-centrifuge.*

The same device is used on a smaller scale and at higher rates of revolution to separate the constituents of blood. Ultra-centrifuges running up to 10,000 rpm cause the watery serum

to be thrown away from the red and white corpuscles. Indeed, this instrument, which looks not unlike a soda-fountain mixer, is most useful for all kinds of biological work requiring the separation of proteins and other substances whose difference in mass is very slight.

J. W. Beams of the University of Virginia had developed a "super-ultra-centrifuge", whose driving mechanism was suspended in a vacuum by magnets to reduce friction to a minimum.* This whirligig could be "revved up" to nearly six million rpm, equivalent to a rim speed of about 3,500 miles an hour! It seemed possible that the gaseous isotopes we are talking about might be separated in this way; in fact, the separation factor would be far higher than in the diffusion method. None the less, the operation would have to be carried out in a long series of stages and a tremendous number of ticklish engineering problems were involved in designing large-scale equipment. It is one thing to construct a centrifuge about the size of a thimble to operate at such an unthinkable velocity; but to build a separation plant equipped for large-scale use of such an instrument is quite another. Preliminary estimates indicated that to separate a sufficient amount of U-235 by this means would require no less than 22,000 separately driven ultra-fast centrifuges—each one three feet long! By the time these figures and cost esti-

*_Time_, January 13, 1941, p. 44. The instrument broke down at 6,000,000 rpm.

mates for installation were arrived at, other methods were so far along that the centrifugal separation was not used on a large scale.

However, a pilot plant was set up by the Standard Oil Development Co., at Bayway, N. J. The design and manufacture of large ultra-centrifuges were undertaken by the Westinghouse Electric & Mfg. Co. Some interesting and important work was accomplished, but the experiments were eventually discontinued.

75. Electromagnetic Separation

It was previously mentioned that A. O. Nier had been able to isolate a few micrograms of U-235 by use of the mass spectrograph. The electromagnetic separation method is really an application of the principle of the mass spectrograph on a grand scale. Though for certain technical reasons this method was not considered feasible in early months of the uranium project, and was therefore temporarily sidetracked in favor of gaseous diffusion and centrifugal techniques, it turned out that the sidetrack became the main line of U-235 production.

To clarify the theory of the electromagnetic method, a word must be said about ionization, which was touched upon in an earlier section. It is a rather complicated subject; but all we need to know for this purpose is that when a gas—for example uranium hexafluoride (UF_6) — is

passed through an electric discharge, its molecules separate into atoms of the respective elements, each atom acquiring an electric charge in the process. In this case the UF_6 molecule "dissociates", as the separation is called, into a positively charged atom of uranium (U^+) and negatively charged atoms of fluorine (F^-). What probably happens is that the uranium atom loses *one* of its electrons to each fluorine atom; as a result its internal electrical balance is disturbed. By losing six negative charges (electrons) it has an excess of positive charge; the fluorine atoms, on the contrary, gain an electron and thus acquire an excess negative charge. Such charged atoms are known as *ions*. We are not interested in the fluorine ions, but are very much so in the uranium ions, which of course consist of both $(U^{238})^+$ and $(U^{235})^+$ in the same proportion as usual, namely 140 to 1.

Now when a magnet is brought close to a stream of charged particles in a vacuum the direction of the stream is changed, and the particles describe a semi-circle as they pass through the area of magnetic force. They behave in this way because of their electrical properties. As we have seen, this phenomenon is utilized in the cyclotron. The mass spectrograph also takes advantage of this situation in the following way, as illustrated in *Figure 27*. If a stream of uranium ions, a few of which are slightly lighter than the majority, is passed through a magnetic field so that each ion travels in a semi-

circle, the speed of the heavy ions will be a bit greater than that of the light ones. This being the case, the heavier ions, because of their greater kinetic energy, will inevitably describe a larger semi-circle than the lighter ones, just as in the centrifuge the heavy particles swing a wider circle than the light.

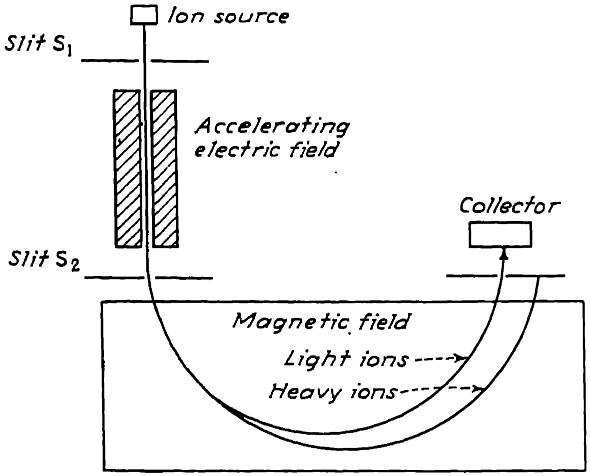


Figure 27. *How isotopes are separated by passing through a magnetic field.*

The mass spectrograph operates in a vacuum. The ions of U-238 and U-235 enter at the slit designated by S_1 in the accompanying diagram. Here they are seized by a strong electric impulse which increases their velocity several thousand times. The purpose of this acceleration is to provide them with so much kinetic energy that their very slight difference in mass will be reflected in their course through the magnetic field, which

they enter through slit S_2. The U-238 ions, traveling at tremendous speed, traverse a wide arc through the field; but the few U-235 ions, being lighter, have just enough less momentum to cause them to describe a narrower semi-circle and so to be caught in a collecting device placed at the end of their course. If the two kinds of ions were not "kicked along" en route, their extremely slight difference in mass would not be sufficient to separate them in this manner.

Although there are several drawbacks to using the electromagnetic method on a large scale—principally the difficulty in ionizing the gas in sufficient quantities and the fact that only a small part of the ions produced are actually used—these were overcome to a great extent by subsequent research. It differed from the other methods described in one important respect: there was no question about its feasibility. It would work with predictable efficiency if the necessary equipment were provided. This included huge magnets, high electrical voltages and pumps for maintaining a high vacuum. Moreover, there would be no need for an elaborate series of stages, because the separation factor is much higher than in the gaseous diffusion and centrifugal methods; a few stages, or possibly only one would be necessary.

The production research was done at E. O. Lawrence's laboratory at the University of California, utilizing the magnet taken from the 37-inch cyclotron. With this Lawrence set up

what he called a "calutron", which was a large-scale device built on the principle shown in the foregoing diagram. Experiments with this instrument showed that it was possible to concentrate the stream of ions more efficiently than had been anticipated and that atoms of U-238 and U-235 could be segregated with definite precision. Still, even on this scale there was no hope of obtaining any important amount of U-235—a far larger and more powerful unit was required, which could produce grams rather than milligrams. Fortunately, a huge electromagnet—at that time the largest in the world—destined for Lawrence's proposed 1,000-ton cyclotron, was in process of construction at Berkeley, though work on it had been delayed by the outbreak of the war. This was just what the doctor ordered for further development of the separation project. The magnet was rushed to completion, and most of the remaining problems were ironed out.

An electromagnetic separation plant was set up near Clinton (Oak Ridge), Tennessee, in the spring of 1943, on the basis of the research done with the huge magnet at Berkeley. This plant was the first to give significant quantities of U-235. Five concerns shared the responsibility for the final installation: the mechanical equipment was supplied by Westinghouse, the electrical and control instruments by General Electric, and the magnets by Allis-Chalmers; construction was carried out by the Stone and Webster

Engineering Co., and the plant was operated by the Tennessee Eastman Co.

In addition to the gaseous diffusion, centrifugal and electromagnetic separation methods there are four others, namely, those based on thermal diffusion, distillation, exchange reactions, and electrolysis. Only the first of these was worked out on a large scale. A thermal diffusion plant was installed at Clinton in 1944, to operate in conjunction with the electromagnetic plant. The theory of this separation method is based on the effect of a temperature gradient; that is, if the mixture of isotopes is admitted to a chamber one part of which is hot and the other cold, one kind of isotope will tend to collect in the high-temperature portion, and the other in the low-temperature portion. As the details are somewhat complicated, no further description of this system will be given.

76. The Turning Point

We have now briefly surveyed the three most interesting methods of obtaining pure U-235, which at the initiation of the bomb project in December 1941 seemed highly essential. As this was one of the two major lines of endeavor, a few of the practical production problems have been touched on to give some conception of the scale and magnitude of the undertaking, as well as of the vast amount of meticulous and exacting research that had to be done all along the

line. In order to pursue this phase of the project consistently, we were obliged to leave the even more urgent matter of plutonium production high and dry. It is to this more unusual and in some ways more interesting subject that the remainder of this resumé will be devoted.

As mentioned previously, the chronology of the various undertakings is almost hopelessly entangled. However, one date emerges as being of real significance—the latter part of 1942. It was then that most phases of experimentation ended and that large-scale production units were decided upon. Such decisions naturally had to be based on the results of the small-scale work that had then been achieved; there was no time for extended pilot plant tests and all the elaborate control work usually associated with the introduction of a new process. Here several entirely new—some would have said impossible—processes had to be set up and started within a few months. Risks had to be taken and much courage was necessary: 1942 was the year of decision for the whole atomic energy development.

We shall now go back and pick up the history of the experimental and development work on chain reactions and the large-scale production of plutonium. As previously mentioned, these two possibilities—namely, that of a continuous, self-sustaining chain reaction and conversion of U-238 to the highly efficient plutonium—had been envisaged before the atomic energy project

got under way; but at that time they were little more than theoretical assumptions based on Fermi's work at Columbia. First it had to be proved that a uranium-graphite system could actually be set up in which the all-important chain reaction could be maintained; then the feasibility of large-scale plutonium formation had to be explored. Over a year of intensive research was required on these two aspects of the problem, which constituted the second major objective of the atomic energy program.

77. *The First Experimental Pile*

IT WILL BE recalled that in order to attain the maximum number of direct neutron hits on the U-235 nucleus, it had been found necessary to retard the fast neutrons by passing them through a graphite "moderator." Thus slowed up, the neutrons are unable to penetrate the U-238 nuclei, and their loss by capture is avoided. It is possible to use other substances as moderators; indeed the first technique for "slow" neutrons involved passing them through water or paraffin which retard neutrons because of their high content of hydrogen. The Germans were experimenting with heavy water for this purpose, and were maintaining a plant in Norway for manufacturing it. Some trials were made here also, and a test pile of uranium and heavy water moderator was later constructed at the Argonne Laboratory in Chicago. But for practical pro-

duction, it seemed better to have a solid material in which chunks of uranium could be imbedded; and highly purified graphite was about the only choice open.

In July of 1941, Fermi and his associates at Columbia constructed the first so-called "pile" of uranium oxide and graphite for the purpose of making measurements of its chain-reacting possibilities. It was in the form of a cube eight feet on an edge; the structure was built up of blocks of graphite, in which at regular intervals were placed iron cans containing a total of seven tons of uranium oxide (no highly purified uranium or graphite was available at the time). A source of neutrons for bombarding the lattice was placed near the bottom of the pile; this consisted of beryllium which was subjected to a stream of alpha-particles issuing from a radium salt. As we have seen, beryllium is an excellent source of neutrons.

Just to be sure that the theory is clearly understood, let us recapitulate for a moment. The idea is that the neutrons ejected in great numbers from the beryllium target inside the pile will penetrate it at all points; by far the larger number of them will pass through the graphite, which will greatly retard their speed. A few will strike the pieces of uranium almost immediately, without being appreciably slowed up; most of these will be captured by U-238, though a few may cause fission. Many will be lost to impurities in the graphite, and some will leak out of the pile.

But it is the action of the *slow* neutrons that is of primary importance. Traveling through the graphite they lose so much speed that by the time they reach the chunks of uranium they are unable to enter the stable U-238 nuclei; the few unstable U-235 nuclei, however, receive them with great promptness and gusto. Almost all of them split, releasing their great energy and two or three neutrons as well. These new-born neutrons, being of the fast variety, then proceed to bombard the U-238 nuclei which surround them. The trouble is that most of them fail to make direct hits and so are lost by capture. Here is the whole problem and purpose of the experimental pile: can the new neutrons created by the slow-neutron fission of U-235 nuclei become numerous enough to exceed the rate at which they are captured by U-238 nuclei and impurities? If so, a self-sustaining chain reaction will occur. Mathematically speaking, the neutron "multiplication factor" k must be greater than 1.00 to maintain chain-reacting conditions. This factor is the ratio of the number of fission-produced neutrons to the number of neutrons originally present.

Also it must be noted that when a U-238 nucleus captures a fast neutron it becomes U-239 and is on its way to becoming plutonium, which is even more fission-sensitive than U-235. Thus the early piles had a double use; first to determine the practicability of maintaining a chain reaction, and secondly to find out whether

the theoretical possibility of producing plutonium could be brought to fruition.

The original uranium lattice at Columbia did not answer these questions; it was too small to provide conclusive results, and the materials used were too impure. However, many invaluable data were obtained on rate of neutron transmission, location of uranium concentrates, and the exact neutron count. The possibility of enclosing the pile with a beryllium "reflector" to decrease the number of escaping neutrons was suggested, but the critical scarcity of metallic beryllium made this out of the question. Graphite reflectors were later used.

One question which should be settled is "Why doesn't the uranium lattice explode if all this energy is being released?" For the same reason that a piece of radium or other radioactive element doesn't explode, or that a piece of dynamite burns quietly in the open air. As a matter of fact, both the radium and the dynamite do explode, but they do so at such a gradual rate that no harm results. The key to the answer is the word *rate;* the fission reactions in a uranium lattice are so slow that the energy released is given off as heat and radioactive emanations. As long as a cooling system or control rods are provided there is little chance of an explosion. But an extremely close watch is kept on the rise of temperature in the system, particularly when it is known that a chain reaction is or may be in progress. Again the word *rate* should be emphasized.

A slow chain reaction is inadequate for military purposes: what is wanted is one which will tear through the atoms of uranium like a flame through gasoline-soaked excelsior; for it is the rapidity with which the nuclear energy is released that governs the destructive effect.

78. *The First Chain-Reacting Pile*

By the latter part of 1942 methods for obtaining pure uranium metal and graphite had been developed sufficiently to permit construction of a more ambitious lattice upon which all hopes were centered. The work was carried out as before by the Columbia group headed by Enrico Fermi. Partly for secrecy reasons and partly for geographical convenience the site of this pile was the floor of a squash court located under the west stands of Stagg Field at the University of Chicago. It was constructed in approximately the shape of a doorknob, with the purest materials at the center. It contained about six tons of uranium provided by the new purification techniques and produced by Westinghouse, Metal Hydrides, and at Iowa State College at Ames.

Previous computations had indicated the number of layers of graphite bricks and uranium slugs necessary to induce a chain reaction; but it was found by means of neutron and radiation counters that the critical size—that is, the size at which the multiplication factor would exceed 1.00—was somewhat less than had been

predicted. The pile as a whole consisted of three lattices: at the center was that containing the pure uranium imbedded in blocks of graphite; this was calculated to give a k factor of 1.07; outside of this were two lattices of graphite and uranium oxide predicted to have k factors of 1.03 and 1.04. These factors turned out to be too low; therefore the pile was made smaller than originally planned. Constant measurements of the neutron activity within the pile were made during construction, so that the point at which the multiplication factor would exceed 1.00 could be foretold before it was actually reached.

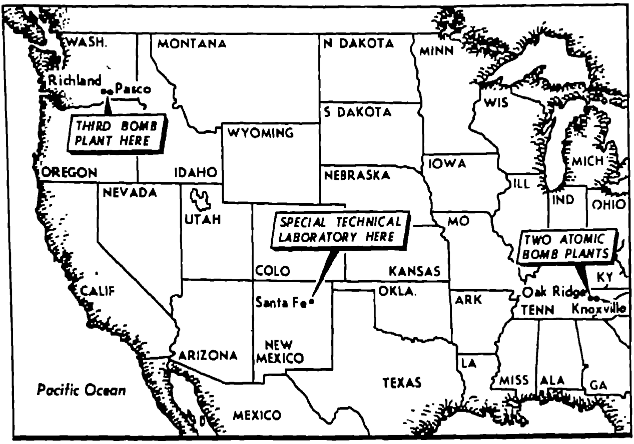
The method of controlling the rate of neutron production is quite interesting—indeed it was a most fortunate fact that any sensitive means of doing so was found; otherwise, no large-scale piles would have been possible. The truth is that nothing more complicated than a few narrow strips of cadmium metal are sufficient to keep activity well below the point where $k = 1.00$. So extremely sensitive is this control method that the pile can be started by removing all but one of the strips and then carefully adjusting the last one. Even moving it as little as an inch or two when the system is near the critical point is all that is necessary to start or stop the chain reaction. In this way the intensity of neutron production and the rapidity of the chain reaction can be governed to a hair's breadth.

The energy produced by the pile was also closely controlled by this means. It could be held

to as little as half a watt, or run up to 200 watts; this was the highest level considered safe. At this point careful radiation measurements were made close to the pile and outside the building. The energy release was computed on the basis of the rate of neutron production as determined by counting devices. The performance of this pile conclusively proved that controllable, self-sustaining nuclear chain fission was possible with a uranium-graphite lattice.

79. The Plutonium Problem

There are many astounding facts relating to the installation of production and separation plants for plutonium; but the most astounding of them all is that the staggering problems of design and engineering involved were successfully solved on the basis of the knowledge gleaned from about half a milligram of plutonium—a quantity so small that if you had it under a fingernail you would scarcely notice it! The experimental pile at Chicago produced no plutonium whatever, though it indicated that this was possible; the one tiny sample in existence had been made with the huge cyclotron at Berkeley, California. The Chicago trials showed that at an energy output level of 200 watts—the highest that could safely be attained there—the pile would have to run for something like 70,000 years to make enough plutonium for a single atomic bomb! It was essential therefore



Press Assoc., Inc.

Figure 28. *Map showing the plants where plutonium is being produced, and the laboratory established to develop construction of the bomb itself.*

to plan units large enough to attain an energy output of at least 1,000 kilowatts—no less than five thousand times that of the Chicago pile; the wattage, or "power level", is merely a convenient way of expressing the heat produced in the lattice by uranium fission. It was also equally necessary to build plants to separate the pure plutonium from the uranium after it had been formed in the pile.

The complicating factors were many. In the first place, the whole problem of pile design and control was hydra-headed. In the second place, plans had to be laid and decisions reached for setting up *two* plutonium plants at once: a relatively small one (1,000 kilowatts) to be located at Clinton (Oak Ridge), Tennessee, and a full-

scale pile at Hanford, Washington, to operate at from 500,000 to 1,500,000 kilowatts. Time was so short that little benefit could be derived from experience gained with the smaller plant in constructing the larger: the two had to be designed and put into operation almost simultaneously. As a result of this time factor, a phenomenon unique in the history of chemical engineering took place: a production-scale installation was designed, laid out, and well on its way to completion before as much as a gram of its product was in existence! But the successful accomplishment of this gigantic task was by no means just a lucky break; it was achieved somewhat in the same way that a trained aerial navigator could direct a plane to a small island whose general location he knew, even though no one had ever been there before, by the laws of trigonometry and navigation and such scraps of specific data as he could gather en route.

The design and construction of the two plutonium plants—the smaller at Clinton and the larger at Hanford—were undertaken by the E. I. du Pont de Nemours & Co. on a cost-plus-fee basis—the fee being $1.00. It was also understood that no patent rights of any kind should accrue to this company. Du Pont technicians worked in close contact with the staff of the Metallurgical Laboratory in Chicago. The chief purpose of the smaller installation was to develop the "know-how" for the production and chemical separation of plutonium; some of the

results obtained here came through in time to facilitate construction of the later Hanford units. Here again it may be mentioned, to emphasize the difficulty of the task, that the first production and separation plants at Hanford were far advanced before a single atom of plutonium had been made and separated at Clinton.

80. *The Lattice*

TO BRING ABOUT the formation of plutonium, it is necessary to have a chain-reacting lattice. As we have seen, slow-neutron fission of the U-235 present provides a source of fast neutrons which are captured by U-238 nuclei, thus forming U-239; this becomes neptunium by disintegration of one of its neutrons into a proton and an electron, the latter being radiated off. Shortly after this, the process is repeated with the neptunium, and the comparatively stable plutonium, of atomic weight 94, is formed. About two and a half days are required for the cycle. Since this releases a tremendous amount of heat, adequate provision for cooling was one of the primary considerations of a large-scale pile. Moreover, since the uranium containing the plutonium formed must be removed from the pile at regular intervals, it was necessary to devise some practicable way of doing so without dismantling the entire structure.

These two essential considerations—cooling and product removal—virtually dictated a radi-

cal change in the lattice structure. The uranium in the Chicago pile had been in the form of lumps imbedded in the corners of the graphite blocks. It is obvious that the heat concentration will be extremely high in the vicinity of the reacting lumps—too high for safety in a pile operating near 1,000 kilowatts. Furthermore, removing the lumps would mean taking the entire lattice apart. In order to provide for both these difficulties, a "rod" lattice was planned: instead of scattered chunks of uranium placed at points throughout the lattice there would be long horizontal channels in which metal rods containing the uranium were placed. These would have to be arranged so that the rods could be withdrawn when the plutonium-forming reaction was judged to be complete, and fresh ones slid in; and this meant that the pile would have to be cubical rather than oval. Effective multiplication factors for this arrangement had to be determined, in view of the neutron-capturing proclivities of the metal used for the rods.

Inserting the uranium in rods or cylinders was the solution of removal difficulty, but it only partially met the cooling problem. It was clear that auxiliary cooling would be necessary. The methods adopted, which differed in the two plants, will be mentioned presently.

81. Shielding and Control

The highly radioactive condition of the material would make it impossible for anyone to

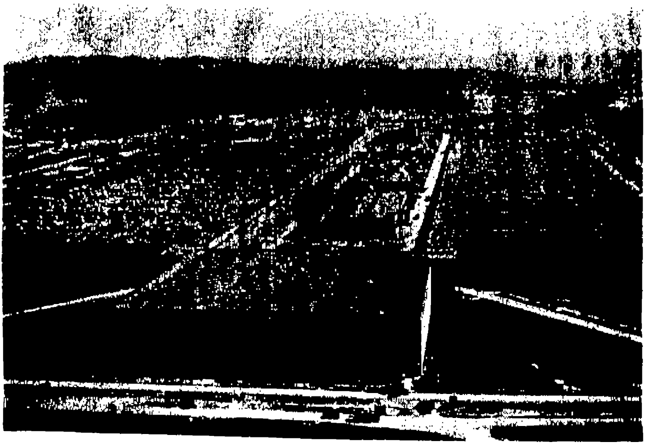
come near enough to put in and take out the rods of uranium. This posed another neat little problem: imagine trying to operate an installation requiring rapid and accurate handling of bulky materials without a human hand coming within yards of it! But this did not daunt the physicists and engineers; they worked out a method whereby all the putting in and taking out, including subsequent removal to the separation unit, were performed by remote control—presumably by electronic setups — from behind thick concrete shielding barriers. Operation of both plants is fully automatic; few of the supervisors and none of the workers ever see the unit while it is running, much less approach it. These barriers must be both radiation-tight and air-tight—the former to absorb the neutrons and gamma rays which are constantly leaking out of the lattice, and the latter to prevent outside air from getting in and being made radioactive by contact with it. These shielding difficulties applied to the separation as well as the production units; at every turn the lethal radiation had to be sealed off, absorbed, or dissipated—it could never once be disregarded, either in its immediate or long-range effects. This, rather than explosion of the pile, was the ever-present, insidious peril.

As mentioned in describing the Chicago pile, the exact level of energy output, neutron count, and other essential data are under the most

ılous automatic control. This is achieved ·ious types of instruments located within le, the determinations of which are of : relayed to a complicated array of record-arts outside. Emergency controls such as um- or boron-steel rods are also provided stantaneous insertion if the power level l exceed a predetermined rate. By means recording instruments any defect in the g system, incipient lowering of the multi-:on factor, or other variation from estab- pile performance can be immediately d. All the necessary wiring is carried in gh the air-tight concrete walls.

82. *The Clinton Installations*

SITE WAS selected because of its prox- to the huge power supply created by Tennessee Valley Authority; it became n as the Clinton Engineer Works, and had originally acquired by the government for ntire atomic energy project. But later de-ments indicated that it was not sufficiently ed for a plutonium production plant of the equired, because of the possible contamina-f the area by radioactive products. In addi- the supply of water for a cooling medium, 1 had been decided on for the large plant, inadequate. For these reasons only the er of the two projected plutonium piles was lled here. Its purpose was mostly experi-



Press Assoc., Inc.

Figure 29. *Air view of plutonium pile at Clinton (Oak Ridge), Tennessee.*

mental. Designed to operate at 1,000 kilowatts, it was a cube-shaped rod lattice, the uranium being sealed into gas-tight aluminum sheaths which are passed horizontally into channels in the graphite. Aluminum was chosen because it is a good heat conductor, does not absorb neutrons readily, and is highly resistant to corrosion. The problem of finding the best metal for "canning" the uranium and of obtaining gas-tight seals was just one more time-consuming obstacle, and its solution involved a vast amount of research. This lattice was artificially cooled by air which circulated through the graphite in the channels containing the rods. It was considerably larger than the Chicago pile, and operated satisfactorily at its designed power level. The

first plutonium ever made (except the original half milligram) came out of this pile.

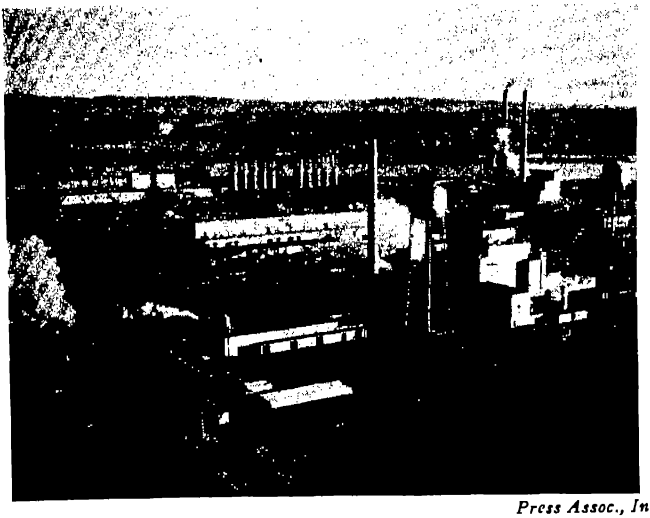
But this was by no means the only installation at Clinton. The chemical separation plant, which is an integral part of the unit, was also in operation here. It consists of a series of concrete cells about 100 yards long, and about two-thirds sunk into the ground. After removal from the lattice, the slugs containing newly formed plutonium, as well as considerable unchanged U-238 and a host of radioactive fission elements, are moved under water to the beginning of the line of cells, and are then processed by remote control. The matter of reclaiming the unconverted U-238 for re-use was given considerable attention and a technique for accomplishing this important operation has been recently perfected. The waste gases from the separation plant containing the dangerous fission products are disposed of by high vent stacks; so far no adverse effects on the adjacent countryside have been reported.

It may well be imagined that knowing just when to shut down the chain-reaction so as to obtain the best yield of plutonium would be quite a problem. In fact the necessity for determining this point was one of the purposes of the Clinton pile. It can scarcely be explained here because of secrecy requirements, though it can be stated that the reaction is stopped long before all the U-235 in the lattice has undergone fission, which means that the ratio of plutonium formed to unconverted U-238 is quite low.

In addition to the plutonium plant, large-scale installations for separating U-235 by the electromagnetic, gaseous diffusion and thermal diffusion processes were located on the site of the Clinton Engineer Works.

83. The Hanford Plant

The location of the Hanford installation was selected primarily because it combined the requirements of isolation and a plentiful supply of cooling water. The original plan had called for the use of helium for this purpose, but it was finally abandoned in favor of water, chiefly because of the limited supply of helium. The introduction of water into the piles created a host of new difficulties; it could not be allowed to come into contact with the uranium because of the reaction that would occur between the two substances: radioactive material would be absorbed by the water to such an extent that the uranium would disintegrate. So much energy would be released by the pile, moreover, that only a "once-through" circulation of water was possible. The quantity necessary to carry off thousands of kilowatts would be enough to supply a good-sized city. As the out-going water would be radioactive enough to be hazardous to communities farther down the river, plans had to be made to retain it for a time in effluent basins. Complicated systems of pumps, filtration plants and other incidental requirements had to be in-



Press Assoc., Inc.

Figure 30. *Plutonium separation plant at the Hanford Engineer Works.*

stalled. The selection of aluminum as a coating material for the rods of uranium has been mentioned; it was also used to pipe the cooling water through the pile. In addition to its corrosion- and leak-proof properties, aluminum has the lowest neutron capture cross-section of any metal that could have been used; naturally the extent to which it absorbed neutrons had to be carefully worked out in advance, to insure an adequate neutron multiplication factor in the pile.

Construction of the Hanford Engineer Works was begun in June of 1944, and the first of the three lattices comprising the plant started production three months later. By the middle of

1945 all three were in operation, each of course having its own plutonium separation plant. All of the major units were widely separated, and shielded in concrete, in the same manner as at Clinton. During the period of construction, which required a vast amount of shoveling, cement pouring and all the manifold activities of a major plant installation, this previously deserted locality became the temporary home of 60,000 people, with the usual complement of stores, theatres and restaurants.

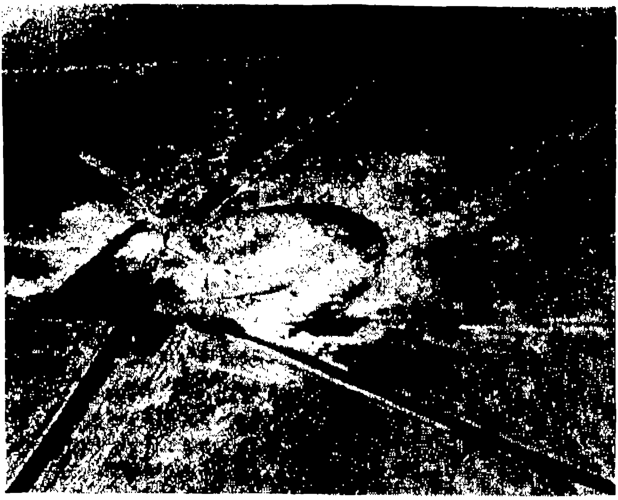
It must not be supposed, however, that huge production units such as those at Hanford are difficult to operate or that they require a small army of workmen. On the contrary, once set up and started, they need only supervision by a few experienced men. They are about as completely automatic as any industrial operation yet devised. About all that is necessary is to watch the dials and charts to be sure there is no break in the cooling system, and to set in motion at the proper time the various remote-controlled unloading and reloading mechanisms; progress of the unloaded material to the separation unit and its processing there is also largely a matter of recording instruments and push buttons.

It is not only remarkable but phenomenal that no major difficulties occurred which could be attributed to poor planning, faulty workmanship or miscalculation. Stupendous as the original obstacles were—and by no means all of them have been mentioned in this brief survey—once

they had been overcome there was no hitch of any consequence. This fact is a tribute to the genius and hard work of all those who shared the responsibility for installing the first large-scale atomic-energy plant in history.

84. Los Alamos, New Mexico

As far as the military objective was concerned—and this of course was the prime consideration—all the work so far described was merely preparatory to the final climax, the atomic bomb itself. The purpose of the elaborate and painstaking isotope separation plants was to provide a sufficient supply of the rapidly chain-reacting U-235: the vast and incredible complications of the slow chain-reacting piles were attacked and surmounted because of the superior explosive properties of the new element plutonium, which does not capture fast neutrons as readily as U-235 and thus inhibits the chain reaction to a considerably less extent. In all these processes the greatest care had to be taken to prevent a rapid rise in the multiplication factor, which would have resulted in a catastrophe beyond measure. Now the problem was to devise a means not only of producing such a catastrophe, but of so controlling and timing it that it would occur at precisely the right instant. If the bomb were to explode a little too soon its effectiveness would be greatly vitiated; if it should turn out to be a dud, the enemy would be in possession of



Press Assoc., Inc.

Figure 31. *Air view of the site of the atomic bomb test blast reveals stubs of towers (center), 300-foot diameter crater, and 2400-foot diameter (blacked area).*

the means with which to return the compliment. Never was the need for mathematical exactness more compelling!

The site of the atomic bomb laboratory was chosen on the basis of secrecy and isolation. On a lonely stretch of desert about twenty miles from Santa Fe has arisen in a little over two years what Professor Smyth says "is probably the best-equipped physics research laboratory in the world." Nothing was there; everything had to be brought and installed. "Everything" included three carloads of apparatus from Princeton, such knick-knacks as a cyclotron from Harvard, and ponderous high-voltage equipment

and accessories from other distant points. The laboratory was under the direction of J. R. Oppenheimer, and the personnel included scientists from the Universities of Chicago, California, Wisconsin, Minnesota, Princeton, and Harvard. In addition, J. Chadwick, the discoverer of neutrons, headed the delegation of British physicists present, and Niels Bohr of Denmark visited the laboratory and contributed greatly to the results.

85. The Critical Size Factor

No self-sustaining chain reaction is possible, either in U-235, plutonium, or a lattice unless a certain quantity of fissionable material is present. Though it is possible to split nuclei of uranium and release 200 million electron volts of energy per atom, no explosion is obtained unless there is enough active substance to allow an effective neutron concentration to be built up by a succession of fissions.

There is a very definite minimum size for a chain-reacting lattice, which can be reduced somewhat below the theoretical point by enclosing it in graphite barriers, which reflect escaping neutrons back into the system. This principle is also used, as we shall see presently, in limiting the size of the bomb. The quantity below which one cannot go without reducing the factor k to less than 1.00 is called the *critical size* governing the chain reaction. It is very close to two kilo-

grams or 5 pounds, of U-235 or plutonium. On the other hand, once this quantity has been reached, the chain reaction inevitably follows, as it can be initiated by the stray neutrons in the atmosphere resulting from cosmic rays, or by spontaneous fission within the body of the material. It is worth emphasizing once more that the critical size of a bomb is controlled by the ability of the fission-produced neutrons to become numerous enough to exceed loss by capture, escape, and residual impurities.

Essentially, then, the crux of the detonation problem was to keep the 5 pounds of reactive material in separate pieces within the bomb, and then to make them unite rapidly at just the right moment; the increase of the *k* factor in the resulting mass would do the rest. The efficiency is increased by use of a "tamper" to prevent escape of neutrons from the unit. This may be made of any material of high density, such as lead. The tamper also contributes to a more destructive explosion, as it tends to prevent the bomb from flying apart before a high energy content is achieved.

86. The Time Factor

IT HAS BEEN stated that the effectiveness of any release of energy is inversely proportional to the length of time required for the reaction to occur. The energy delivered by an automobile in stopping is likely to be more destructive if the

stopping is done by a tree in one-tenth of a second than by the brakes in five seconds, even though the total is the same in both cases. Similarly *slow* combustion of an explosive is relatively harmless, whereas almost instantaneous combustion is devastating. This consideration of time is just as valid for an atomic bomb as for any other kind; after all we are dealing with energy, and with the laws controlling it, notwithstanding the fact that its source and quantity are new.

Thus there are *two* vital time factors in the control of an atomic bomb explosion: first, the time required for the separated units of U-235 or plutonium to get together to start the chain reaction; this should be as short as possible. Secondly, there is the time lapse between this event and the disintegration of the bomb. Naturally, it will fly apart just as soon as enough explosive force to burst the casing has been generated in the interior; and the intensity of the explosion will be diminished the instant this happens, because the rate of reaction will be greatly retarded. To realize the maximum of destructive efficiency, if such an expression is permissible, the time interval between the start of the reaction and the disruption of the bomb should be long enough to permit as large an energy concentration as possible to be built up in the bomb before it flies apart; otherwise the explosion will fizzle out. The greatest difficulty encountered in making the bomb effective was

due to the extreme brevity of this interval. Reduced to chronological terms, what happens is this:

(1) The separated bits of reactive substance are forcibly united within the bomb;
(2) The chain reaction starts, and increases to a certain point at which
(3) The bomb casing bursts;
(4) The chain reaction continues until stopped by dissipation of the material.

The crucial time intervals are between (1) and (2), and between (2) and (3); in Professor Smyth's words, "the parts of the bomb must not become appreciably separated before a substantial fraction of the nuclear energy has been released." To insure correct time coordination involved in union of the packets of U-235 on one hand and the interval between the start of the reaction and disintegration of the bomb on the other was a problem of the first magnitude. It is essential that the first of these events be as rapid as possible, because the chain reaction can be started by stray neutrons before the units of U-235 have had time to unite; if this occurs the bomb will fly apart before complete union takes place, and the explosion will be far from efficient. To this end, stray neutrons must be reduced to a minimum.

It is evident that we are dealing here with inconceivably short spaces of time—to the casual observer the events are simultaneous. No official figures have been given as to the actual

time lapses; but it has been estimated that the total interval from (1) to (4) inclusive is in the neighborhood of one-millionth of a second! The frightful force of the explosion is largely due to this fact.

The problem of assembling the pieces of U-235 was of paramount importance. As long as they are well separated, the number of stray neutrons escaping is too small to cause trouble; but as they approach one another the concentration of neutrons would build up very quickly and

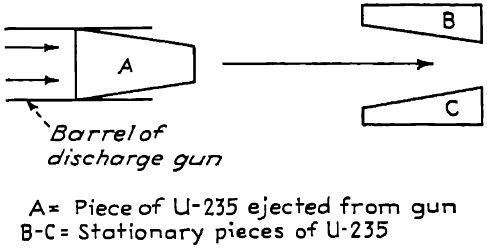


Figure 32. *How the uranium charge is probably detonated in the atomic bomb.*

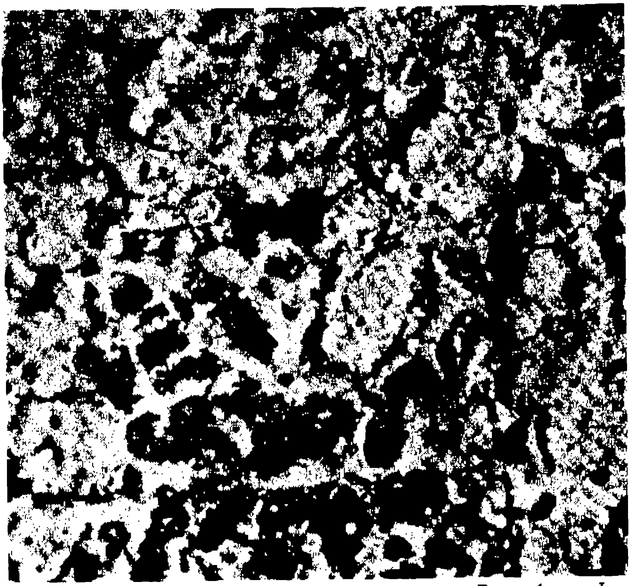
detonate the mass before the most effective size was reached. For this reason it was absolutely necessary to make the pieces join as nearly instantaneously as possible. The most practical way of doing so was to hold two of them steady and have the third retained by some sort of gun or trigger mechanism set to go off at a predetermined instant and thus propel the third piece into position. How this was probably accomplished is suggested in the diagram.

The successful predetermination of all these factors was the task of the workers at the Los

Alamos laboratory. It probably sounds sufficiently complicated from the little that has been said. Yet it was even more difficult than this account indicates, for a welter of problems, experiments, and calculations of neutron density, effective captive cross-sections, angles of deflection, and above all neutron velocities had to be made. Specific details of the construction of the bomb are withheld, and many questions which are of interest are unanswered. Much of the research carried on involved theoretical physics of too high an order for such a resumé as this.

87. The Atomic Bomb Explosion

THE ATOMIC BOMB is detonated when it is about a thousand feet in the air, and is parachuted down. The purpose of this procedure is twofold: first, the greatest possible demolition effect against buildings is obtained, as relatively less of the energy is expended in digging a hole in the ground than in the case of an ordinary bomb; secondly, in this way the radioactive products tend to be carried aloft by the updraft of the explosion, rather than driven into the earth to create a lethally radioactive area. In spite of this precaution, some induced radioactivity will occur, and it was reported that as long as a month after the bombs dropped on Honshu, deaths were occurring as a result of exposure to the bombed locality. In the proving test in



Press Assoc., Inc.

Figure 33. *Sand fused to glass-like structure where test bomb exploded in New Mexico.*

New Mexico, however, it was found that "only a very small fraction of the radioactivity was deposited immediately below the bomb." Notwithstanding this, however, the area gave evidence of radioactivity when tested nine weeks later with a sensitive radiation detector.*(Fig. 16)*

The intense heat and light produced by the explosion are caused, of course, by the release of a small part of the binding energy in the nuclei of U-235 or plutonium. The heat undoubtedly approaches the temperature of the sun's interior at the center of the blast; it is sufficient to turn steel into vapor and to consume every-

thing in its immediate vicinity. The terrific heat also causes rapid expansion of the surrounding air, which creates a violent demolition force. The intensity of the light, too, is comparable to that of the sun: one observer of the test is said to have been temporarily blinded by it. Another factor in the destructiveness of the bomb is the fission products; these comprise a wide range of elements, some of which have quite a respectable mass. A perfect hurricane of these—at least two from every nucleus split in the chain reaction—rages forth, impelled in all directions by the stupendous energy release. Their speed probably is not far from the velocity of light—say about 150,000 miles a second—and the total kinetic energy delivered is inconceivably great. When innumerable trillions of these are on the loose, the result is awe-inspiring indeed!

It is quite true that only about one-tenth of one per cent of the energy in uranium is made available in the atomic bomb; the nucleus is not completely disintegrated, but only divided into two or three parts. Almost all the original binding energy of the U-235 nucleus is preserved intact in the nuclei of the barium, krypton and other product elements. Moreover, only about ten percent of the material in the bomb undergoes fission before the casing bursts. So there is plenty of room for "improvement" merely by devising a way to split *all* the nuclei in the mass of explosive material.

88. Military Future of Atomic Energy

UNQUESTIONABLY THE THREE greatest scientific developments to arise in full effective panoply from World War II are the atomic bomb, jet propulsion, and radar. One scarcely needs the imagination of an H. G. Wells to conceive of the rather immediate prospect that the first two of these will be combined. The idea of radio-controlled stratosphere rockets loaded with plutonium, which could cross the Atlantic in a few minutes, is not pleasant. And if this is not feasible at the moment, it definitely will be within a year or two. The destructive potential of such weapons is so grim, indeed, that we may almost be glad that they are on the verge of reality. From one point of view, they promise such utter and absolute annihilation that it seems impossible that war would ever again be allowed to start. In this sense, these engines of obliteration are a force for peace.

On the other hand, pessimists may point to the time-honored military truism that for every new offensive weapon or tactic a defense is sooner or later developed. If there were to be another war, it would merely mean that the now standard types of fighter and bomber planes would be relegated to the secondary role played by battleships in this war, and that atomic bombs and stratosphere rockets would be the chief offensive weapons. Certain types of radar defense would undoubtedly be perfected against

them; perhaps some means could be devised for detonating them or nullifying their action while in flight. At present, however, scientists who worked on the bomb assert that "there is no defense against it." In the event of another war, the whole concept and practice of global warfare will be stepped up a notch in terror and destruction, as previously happened in the war just concluded.

These are the two points of view, and no one can say which is more nearly right. It is certain that the whole military picture will be radically changed.

The effect of the atomic bomb on naval operations has given rise to considerable conjecture. Surely an atomic bomb explosion above water within a radius of half a mile would cause crippling damage to any naval craft, and severe damage would be inflicted within a much wider radius. What would happen if the bomb detonated under water is not so certain; probably the concussion would be sufficient to spring the plates of a battleship half a mile away. One source* has suggested that the radioactivity induced in the water would so corrode the underwater armor of a battleship that the bottom would drop out of it! This seems quite far-fetched; water itself is not readily made radioactive, though the sodium, chlorine and magnesium which it contains are very susceptible.

*_United States News_, Sept. 17, 1945.

However, the temporary effect of radioactivity on metals is not quite *that* severe! Unless heavily damaged, the ship could soon move out of the radioactive zone.

The wide area over which the blast effect of the atomic bomb operates probably means the end of massed armadas like those used in the European invasions and in the Pacific. Warships will have to spread out over a vast reach of ocean, for one bomb dropped in the midst of a fleet sailing in closed order could hardly fail to destroy or damage a dozen or two. This fact in turn raises anew the convoy problem for submarine protection. The solution of this and other tactical matters is for admirals rather than scientists; but it is certain that the atomic bomb will have a profound effect on naval warfare. It is equally certain, however, that surface navies *will not become obsolete!* Says the *New York Times*, "*If the atomic bomb as now constituted can be used as effectively at sea as on land, then there must be a revolution in naval thinking. The most radical ship maneuvers and the best anti-aircraft defense could not protect a fleet from annihilation if the effect of an atomic bomb is as great at sea as on land. But that has not been proved.*"

At present there are some technical limitations upon the use of atomic energy for war. One is the supply of uranium. As this is the basic raw material, only those nations which have deposits of it would be in a position to compete.

Most of the deposits now known to exist are owned by the United States and Great Britain, and Belgium: but others may come to light in China or Russia, as they did in Canada, where extensive outcroppings of radioactive ore were found several years ago. Another obstacle to the extensive development of atomic energy is its tremendous cost and the production and technical effort required. We have seen in the foregoing pages how vast this is. Only a country of great wealth and industrial power could possibly go into it.

Yet there are qualifications to these facts. The most serious one is the possibility that ways will be found to split, or even wholly disintegrate, the nuclei of elements other than uranium—elements so plentiful as to wipe out the scarcity factor completely. It has been mentioned that elements occupying intermediate positions in the Periodic Table have higher binding energies than uranium; hence their nuclei, if split, would yield proportionally more energy, even though the actual amount per atom would be less. This discrepancy is far more than counterbalanced by the relative abundance of such elements as barium and krypton. A more extreme, but not impossible case, is silicon, next to oxygen the most common element on earth. It has been calculated that its nuclei would yield over 13 million electron volts per fission.* Though they have never been disrupted, it may well be that

**Time,* May 12, 1941, p. 72.

with the gigantic cyclotrons of the near future deuterons could be accelerated to the point where they could not only split but completely disintegrate a silicon nucleus. How much energy this would release is problematical, but it would certainly be tremendous. Then atomic bombs could be made out of sand!

This possibility is far more alarming, as far as world destruction is concerned, than any large-scale development of U-235 or plutonium by other countries. After all, any possible future enemies bent on attacking us would know that we also had uranium-derived energy, and probably a much better supply of it than they would be likely to have. Nations do not launch wars in this era unless they feel that they have the jump on their victims in some important respect, as Germany did in air power. Therefore, until some enemy had developed a much quicker and more extensive supply source, he would not be likely to attack us. It is a real probability, amounting almost to a certainty, that other sources of atomic energy than uranium will be found. And the only offset to that threat, as matters now stand, is for us to find it first.

The present laissez-faire situation in respect to atomic energy development is not as it should be. Efforts should be made to provide that control of this development be vested in a centralized authority in the World Security Council, and that all its secrets be shared with our Allies. This would tend to prevent one nation

from getting an advantage over the others; and this in turn would minimize the danger of further military use of this potentially world-annihilating weapon.

Encouraging evidence that the first of these recommendations is being seriously considered is President Truman's statement to Congress* that "the hope of civilization lies in international arrangements looking, if possible, to the renunciation of the use and development of the atomic bomb, and directing and encouraging the use of atomic energy and all future scientific information toward peaceful and humanitarian ends. The alternative may be a desperate armament race which might well end in disaster." The President went on to propose the creation of a United States commission, presumably comprised of competent scientists, to carry forward his ideas and to guide the progress of atomic research. Perhaps the most telling remark in his message was that atomic energy is "a new force too revolutionary to consider in the framework of old ideas." It is not a particularly flattering commentary on human nature that the choice between power politics and intelligent international cooperation should have to be dictated by stark fear!

By an executive order, President Truman recently withdrew from public sale all lands and locations containing deposits of radioactive ores. The ownership of all the uranium in the United

*October 3, 1945.

States and its possessions, except cases "subject to valid existing rights", is thus reserved to the government. It is almost certain that future development of atomic energy, for either military or peaceful purposes, will be government-controlled.

89. Peacetime Future of Atomic Energy

EVER SINCE FERMI's pioneer work with uranium at Columbia, speculations about the utopia in store for us have been the popular pastime of imaginative physicists, feature writers and radio commentators. Since the "breaking" of the atomic bomb story, a flood of new predictions has emanated from the press of the nation, some of them outdoing Jules Verne and Edward Bellamy in enthusiasm. According to some, the handwriting is written large upon the wall for conventional sources of power: there will be no more need for railroads; everyone will want to live in subterranean houses heated and lighted by uranium-derived power; there will be a complete revolution in urban and social life; mankind will no longer be dependent on climate and the fertility of the soil, as all his food can be grown underground by means of hydroponics, and weather can be made to order. It may be that all of these wonders will eventually come to pass, but certainly not for another fifty years or so. About most of them we are frankly dubious.

One of the country's leading petroleum chemists, Dr. Gustav Egloff, Director of the Universal Oil Products Company, recently gave it as his opinion that industrial use of atomic energy is "beyond the foreseeable future." He stated that "an enormous amount of research and development must be undertaken to control atomic energy before it can be harnessed to fit into industry; for example, to be competitive with gasoline as a fuel for motor cars and airplanes." Some of the objections to the substitution of atomic energy for petroleum products will be discussed presently.

A committee to investigate the possible applications of nuclear energy for constructive industrial purposes was appointed late in 1944. Its membership comprises Dr. R. C. Tolman, chairman; Rear Admiral E. W. Mills, with Captain T. A. Solberg as his deputy; Dr. Warren K. Lewis and Professor H. D. Smyth. This committee has already been flooded with suggestions; the general conclusion is, however, that the growth of any nuclear power projects will be slow. Two institutes for further research have been created at the University of Chicago; one of these, the Institute of Nuclear Research, is headed by S. K. Allison, assisted by Enrico Fermi and Harold C. Urey of Columbia; the other, called the Institute of Metals, comprises Cyril Smith, director and Clarence Zener, professor of metallurgy. These committees will

devote their efforts to fundamental theoretical investigations.*

Let us get down to earth and attempt to predict, on the basis of what is now known, the most reasonable uses of atomic energy within the next generation, bearing in mind that years of additional theoretical research and practical experimentation will be required. The long-range possibilities are certainly revolutionary; they will doubtless cause changes in social, economic, and political relationships comparable to those introduced by the steam engine, the dynamo, and the gasoline motor. Yet the effects will be so gradual that it is likely that they will scarcely be noticed, and society will have plenty of time to adjust itself to the new conditions, which may not be so very different from the old ones after all.

What are now the principal sources of the energy that operates factories, runs trains, airplanes and automobiles, heats buildings, and keeps our industrial life going? Obviously they are three: electricity, obtained from generators driven by the energy derived from coal, or from water power; steam, which is also obtained from the combustion energy of coal; and petroleum products, such as fuel oil and gasoline.

It is equally obvious that there is a marked difference between these in respect to the location of the energy source. Electricity is furnished to a wide area from a central power plant, from which a network of exits leads off to sub-

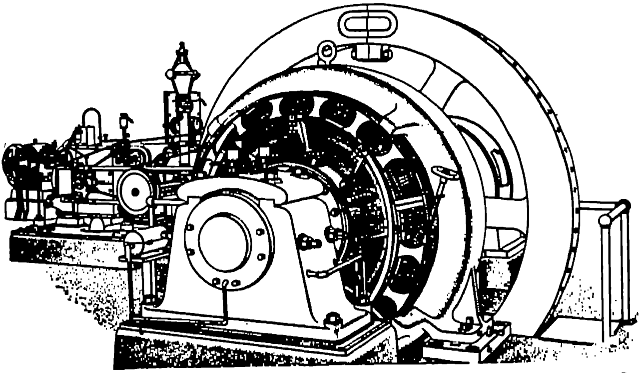
Chemical and Engineering News, Aug. 25, 1945, p. 1444.

sidiary stations and thence to numerous circuits which are tapped at will by thousands of consumers. Diesel-electric locomotives, of course, are an exception to this rule. Steam for heating purposes is not as centralized as electricity; it is usually derived from a boiler in the basement of the building, although in large cities it may be supplied to a number of office buildings from a master generating unit. For locomotives, however, steam must be made on the spot, coal and water being carried along for this purpose. Similarly, all gasoline-propelled transportation units must carry their power source with them in very small quantities; there is no possibility whatever for a remote supply. Thus the centralization of power source is greatest for electricity, less for steam, and impossible for petroleum products.

90. Electricity

WHAT BEARING DO these facts have on future applications of atomic energy? It would seem likely that it might be used first for those purposes which present production facilities indicate—namely, as a source of heat to generate electric power. Here is a point which magazine prognosticators seem to have misunderstood: just because we have, or may soon have, a cheap energy source in uranium there is no need to do away with electricity. It is already possible to maintain a highly efficient slow chain-reacting plant such as the one at Hanford; instead of

using this energy to heat the Columbia River, it seems logical that it might be directed to the production of power for industrial and private use. A half a dozen such plants—which can be made to operate at any desired energy level up to 1,500,000 kilowatts, and possibly more in the future—could conceivably replace all the coal now used for this purpose, given an adequate supply of uranium after allowing enough for



Courtesy International Textbook Co.

Figure 34. *Electric power generators like this may some day be driven by atomic energy.*

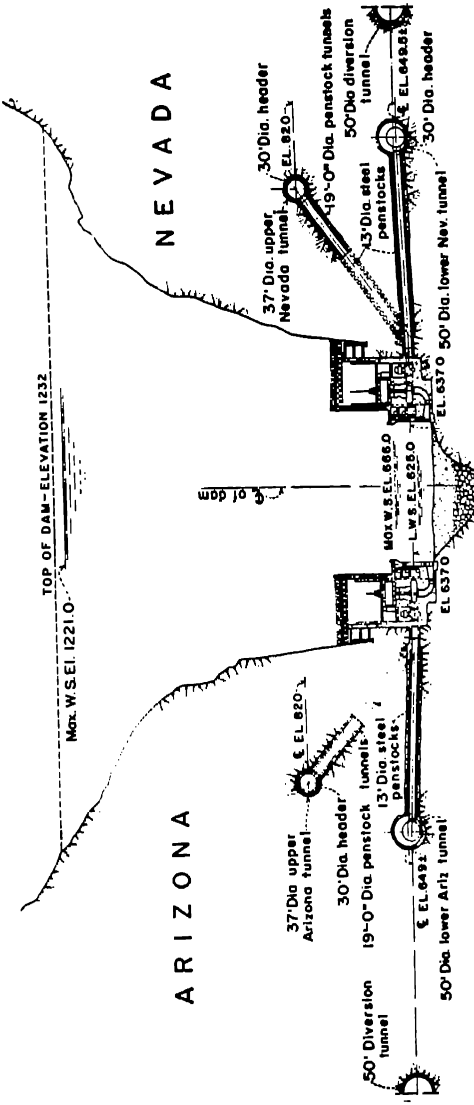
military uses. Once the original cost of materials and installations was retired—which would take a long time—electric power could probably be produced very inexpensively indeed. Eventually buildings and homes now using steam or fuel oil may be heated by electricity for a fraction of the present heating cost. Uranium-power production would be cheap, as it is generated for a long period of time in an automatically con-

trolled pile requiring a minimum of supervision; all the costs now attendant upon the mining and rail transportation of coal, which are substantial items in power production, would be eliminated.

Yet hydraulic energy must not be overlooked. It is a less costly source of electric power than coal, and is utilized to a considerable extent. Not only natural waterfalls like Niagara, but monstrous dams, such as Boulder, Norris, and Grand Coulee, supply power to large areas throughout the country. Comparison of the top power level of the Hanford plutonium pile, which is in the neighborhood of 1,500,000 kilowatts, with the 2,000,000-kilowatt ultimate capacity of Grand Coulee, suggests that uranium-derived energy may not be such a bargain after all! In fact one might hazard the statement that no other source of energy could conceivably compete with hydroelectric power in sections where it is now available. It was used even in Aldous Huxley's grisly utopia.*

Although it is still a speculative situation, largely to be worked out on a cost basis, it appears logical that uranium power installations will eventually be achieved. Experts are generally agreed, however, that it will be a good many years before coal and water power are displaced as sources of electricity. It is true that some of the opinions which have been so widely quoted in the press since the bomb story was

*"Brave New World", p. 119.



Courtesy McGraw-Hill Book Co.

Figure 35. *Boulder Dam. Cross-section through power houses and canyon. (U. S. Bureau of Reclamation)*

released may not be wholly disinterested; even competent scientists have the future interests of their own fields of endeavor to consider. Yet, allowing fully for this personal factor, the cautious and in some cases deprecating note which pervades their opinions on this subject seems fully warranted by the facts now at our disposal. Those who indulge in bizarre predictions about the future of atomic energy are doing a disservice to science and to progress.

91. Steam

WITHOUT STRAINING THE facts too far we can conceive of the use of atomic energy for steam motive power, though whether it could be done cheaply enough to compete with diesel-electric operation is highly questionable. It will be recalled that the first self-sustaining chain-reaction was obtained in the uranium lattice set up at Chicago. The exact size of this pile is not stated, but since it was housed in an ordinary squash court it could hardly have exceeded a diameter of ten feet and a height of eight feet. This pile could be run at a power level as low as half a watt and is easily capable of 200 watts or more. About five times as much energy as this is needed to produce plutonium, but a pile of this size—especially if "enriched" by increasing the amount of uranium—might give energy sufficient for ordinary power purposes. The energy output is precisely controlled by cadmium

strips in the pile, which bring the multiplication factor below the critical point at a moment's notice.

It is hard to see any engineering reason why such a structure could not be erected in the tender of a locomotive. Its energy would heat the water, instead of coal in the fire box, and the propulsion would still be directly by steam. The experiment at Chicago indicated that at the 200-watt level there was not sufficient radioactive emanation to be dangerous within a radius of fifty feet of the pile; notwithstanding this, precautionary shielding would be necessary in a locomotive unit. If located behind the water reservoir, adequate protection of the operators against free neutrons would be automatically afforded. Such an installation would supply fuel equal to that derived from over 100,000 tons of coal—which would run a locomotive for quite a distance!

But there is a catch to this theoretically excellent idea. The Chicago pile contained six tons of purified metallic uranium. To equip 1,000 locomotives would require 6,000 tons of uranium. Whether any such quantity would be available for steam locomotion is problematical; the scarcity of uranium has been repeatedly emphasized. Of course if research proceeds to the point where other substances can furnish energy in such a dependable and controllable way, this restriction will disappear. No uranium pile could be made *smaller* than the approximate dimen-

sions cited above, for these represent the critical size, below which a chain reaction is impossible. Moreover, the difficulty created by radioactive products in the water and their corroding effect on boiler tubes would have to be dealt with, possibly by use of aluminum tubing. This is at least an interesting and not impracticable field for experimentation.

Some publicity has been given to a so-called "atomic locomotive" powered by the "electronic disintegration" of mercury atoms. The proposed arrangement is reported to include a gasoline-driven engine, which runs a dynamo to produce 1,440 volts of direct current; this is discharged into two electrodes in a steel container holding the mercury, the idea presumably being to obtain a high energy output by accelerating the mercury electrons to such an extent that they will exert great pressure. This invention is the work of Ralph Lucas, chief engineer of the U. S. Industrial Research and Development Co. Large-scale tests are planned in the near future. Obviously, since this does not involve nuclear disintegration, it is quite apart from the sort of atomic energy we have been considering. It is interesting, however, to compare this with the possibility of a pile-driven locomotive.

92. Small-Unit Propulsion

Uranium-derived energy to replace gasoline in airplanes and automobiles may some day be

achieved, but that day is probably far in the distance. The car of the future has been envisaged by some enthusiasts as operating on a piece of U-235 the size of a pea in a tank of water, the engine being steam-driven and weighing only a pound or so. There are many serious objections to this. The first is the essential matter of critical size emphasized in connection with the atomic bomb. No sustained energy for mechanical purposes can be obtained from a small piece of U-235 or plutonium, as no chain reaction occurs; and if a large piece were used every car would be a potential bomb! There is no safe means of controlling the reaction of pure U-235 even with slow neutrons. The only practicable means of using atomic energy at present is with the lattice pile whose energy level is closely controlled; this necessitates quite an elaborate installation, possibly workable in a locomotive or an ocean liner, but out of the question in an automobile or airplane.

It would be highly desirable to solve this problem rapidly, because our petroleum resources have been reduced by the war and, though they may last for another twenty years, they will not hold out indefinitely. For this reason some other means of small-unit power supply is important, especially since petroleum has many essential uses in industry and medicine and will some day be too valuable to burn as fuel. The best hope at the moment is discovery of a way to extract energy from some other element, though

even this might pose the same questions. Atomic energy is not a child's toy; uranium is a highly dangerous and insidiously toxic substance, and all manner of safeguards against contamination of the air with neutrons and radioactive products arise when we are thinking in terms of city streets packed with cars.

A fairly safe guess is that there will not be any atomic-powered planes or autos for the indefinite future; and the same reasoning applies to any mechanical unit too small to carry its own chain-reacting pile along with it. A possible exception to this statement is the proposed supercargo and passenger plane capable of carrying heavy loads. But even here the tremendous weight penalty would not make the idea attractive economically.

93. Industrial By-Products

Officials of the Kellex Corporation, subsidiary of M. W. Kellogg Co., recently stated that the fundamental research on the atomic bomb project would release about five thousand new processes applicable to a wide range of industries including petroleum refining, chemical processing and purification, manufacture of pumps, centrifugals and high-vacuum containers, and electrical refrigeration. The knowledge gained in the close separation of isotopes by the gaseous diffusion method, previously described, is obviously of the greatest value to all industrial

processes wherein such separation is important. The same applies to purification of uranium and to plutonium separation. Improvements in the technique of instrumentation and remote-control devices are another case in point. Reporting on the release of this information, the New York *Herald-Tribune* stated: "Mr. A. L. Baker, general manager of Kellex, said that the two major tangible assets accruing to industry are the experience gained in handling hitherto obscure products and the development of new ways of doing business which 'cannot help but result in substantial cost savings and increased quality.' The other major asset he described as the prestige value of the accomplishment, both internationally and in making for 'closer integration of our own scientific world'."

94. Supply and Cost Factors

AT THE RISK of being repetitious, we wish to stress the cardinal importance of raw material supply and cost of extraction and plant installation for such possible peacetime developments of atomic energy as those just mentioned. It is almost impossible to tell in advance to what extent these factors will really control future applications.

As to the supply question, it has been estimated that the earth's crust contains about four parts per million of uranium, most of which is concentrated in specific localities, such as the

Great Bear Lake deposits in Canada, and those in Colorado, the Belgian Congo and Central Europe. It is only such rich deposits as these that are economically workable; once the concentration of metal in the earth's crust drops below a certain point, the cost of extracting it increases rapidly until the quantity obtained is far too small to justify the operation. Just where this point lies for uranium is a question that is impossible to answer now; it will have to be determined by the interplay of economic factors as time goes on. General estimates have been made that the energy available in the total world deposits of uranium ore is enough to supply the power needs of the United States for 200 years, assuming that both U-235 and U-238 are utilized.* This sounds very alluring when cost is left out of consideration, but no such statements mean much by themselves; obviously if it cost $1,000 a gram to extract and purify uranium, we would be better off to go on as we are.

Another aspect of the matter of supply is the great probability that energy may be obtained by discovering how to disintegrate the nuclei of elements that are far more abundant than uranium. If this were done, the supply problem would vanish. Then there is the added qualification that other radioactive elements might be utilized by fission techniques that are now known. The most promising of these is thorium,

*Professor Smyth's report.

which is about three times as plentiful as uranium; but it is not yet definitely known that it can be split with slow neutrons.*

The cost of installing the equipment necessary for large-scale production is another consideration. Undoubtedly the initial investment would be extremely high—so high that, if privately financed,† atomic power might not be able to compete with coal for many years. The situation might be complicated by a reduction in the price of coal-derived power. These questions are economic and financial, rather than scientific. The energy is there and scientists know how to get it out; when, if ever, it will be cheaper than present methods we do not pretend to prophesy.

95. Social Implications

ALTHOUGH WHOLLY DISTINCT from the utilization of atomic energy, the further development and clinical use of radioactive isotopes is sure to be an important by-product of nuclear research. In addition to cancer therapy and medical investigations with the tracer elements previously described, a wide field lies open in many branches of biology for the application of this technique. Much can be learned about the com-

*Professor Smyth's report.

†The question of government *vs* private ownership and operation of any future atomic energy plants is the equivalent of a political atomic bomb! The precedent of the Tennessee Valley Authority could be cited by the proponents of government ownership with telling effect.

plex mechanisms of tissue growth and deterioration in plants and animals; research workers in organic colloid chemistry will find a new and increasingly valuable tool in these temporarily unstable elements. It is too early to make any enthusiastic predictions, however.

Needless to say, the road also is open to discovering more about the physical structure of the universe. Nuclear disintegration has shown us a practical illustration of one of Einstein's most celebrated hypotheses. Perhaps further exploration along these lines will make everyone so conscious of his ideas that they will become as generally understood as those of Newton. People went on thinking that the earth was flat until Columbus and Magellan proved them wrong; but after they accustomed themselves to the notion it ceased to seem strange. In like manner, by means of such achievements as nuclear fission—or possibly some startling discovery in the heavens made possible by the giant telescope on Mt. Palomar which will soon be in operation—we may in a few years be as readily conscious of the fact that space is curved and the universe a spherical entity as we now are that the earth is round. New vistas in education, with all its unpredictable influence on human life and thought, lie before us.

As to the ethical questions precipitated by the atomic bomb, unquestionably the moral sense of mankind will have to come to the fore to establish strict and non-political control over the de-

velopment and use of this ruinous weapon, and to insure that any peacetime applications that grow out of it are not too readily convertible to military ends. This, incidentally, is a truly baffling angle to the problem; for if there are huge atomic energy plants all over the world twenty years from now, the means would be at hand to make enough plutonium in a few days to wreck all the cities in Christendom. It is doubtful whether there is any conclusive answer. The most effective deterrent would appear to be the previously suggested fact that common possession of this power will tend to prevent its military use through fear of reprisal in kind. As a precedent for this we have the failure to use gas by any of the combatants in World War II.

Notwithstanding the fact that the moral sense and education of the people of all nations is the only real hope of preserving permanent peace, the future technical secrets of atomic energy should be pooled among the peace-loving nations and centralized in a supervisory council established under the United Nations charter. Further research should be placed under government control in all countries, and every means should be exhausted to use this great power for the benefit of humanity and not for its destruction. The question is not one of ethics, but of survival.

Viewpoints on the future of a human race possessed of the secret of self-annihilation vary with the individual. Most outspoken of the

recent apostles of doom is Professor Hooton, of Harvard. His study of anthropology has convinced him that man is far from an admirable creature, and that his ethical development proceeds in inverse ratio to his technological skills. He bewails the time and money spent on devising devilish methods of mass suicide, when a fraction of it could greatly improve the human scene by application to eugenics and heredity. In the current mode of expression, perhaps the professor has a point there! Certainly atomic energy, unlimited, is potentially the most hideous force that has been placed in the hands of men.

Yet we need not join Hooton in his pessimism. Civilization is amazingly resilient; wars have come and gone for centuries, each a little more terrible than the last; and it is highly debatable whether the moral sense of mankind deteriorates as his scientific knowledge increases. Society has absorbed a terrific amount of technological progress in both its good and evil phases; it is likely to continue to do so indefinitely.

96. Ave!

THE ABILITY, COURAGE, foresight and hard work of all those who participated in the atomic energy development, both directly and indirectly, are no less worthy of praise and high honor than the exploits of our armed forces in Europe and the Pacific. The magnitude and urgency of the task demanded the highest de-

gree of loyalty and cooperation, as well as technical and engineering genius that was almost inspired. The achievement of the atomic bomb was without doubt the most stupendous and brilliantly executed piece of work in the entire history of science.

Appendix I: Personnel of The Project

So many scientists and institutions took part in the atomic bomb project that it is difficult to single out any for special mention. The following lists, arranged alphabetically, are as complete as possible at the moment. A great deal of assistance was furnished by workers from Canada and England, and constant exchange of information with both countries was in progress during the entire development. Invaluable contributions were also made by scientists of other United Nations countries, notably by Neils Bohr of Denmark and F. Joliot of France.

The so-called Top Policy Group comprised President Roosevelt; Vice-President H. A. Wallace; Secretary of War H. L. Stimson; General G. C. Marshall, Chief-of-Staff; Vannevar Bush, Director of the Office of Scientific Research and Development (which included the National Defense Research Committee); and James B. Conant, President of Harvard University. The uranium section of the O.S.R.D. as constituted in May, 1942, included J. B. Conant, Chairman, L. J. Briggs, A. H. Compton, E. O. Lawrence, E. V. Murphree, and H. C. Ur- with H. T. Wensel and I. Stewart as tec aides. A consulting committee comprise Allison, J. W. Beams, G. Breit, E. U.

and H. D. Smyth. In September, 1942, Major General L. R. Groves of the Corps of Engineers was placed in charge of all Army activities in connection with the Manhattan District Project. Technical and engineering matters were assigned to a Planning Board, which was also responsible for materials procurement and plant construction. This board included E. V. Murphree (Chairman), W. K. Lewis, L. W. Chubb, G. O. Curme, Jr., and P. C. Keith. The purely scientific problems were distinct from this; these were handled by program chiefs H. C. Urey (Columbia), E. O. Lawrence (California), and A. H. Compton (Chicago). G. P. Pegram was also active in various capacities. The personnel of the various committees changed so frequently during the four-year period that it is extremely difficult to keep track of them.

Here are the names of the individuals and institutions that made the success of the project possible:

F. T. Barr
F. H. Abelson
K. F. Adamson
E. Adler
P. C. Aebersold
W. A. Akers
S. K. Allison
L. Alvarez
H. L. Anderson
H. R. Arnold
F. W. Aston
P. Auger
R. F. Bacher
J. G. Backus
K. T. Bainbridge
J. W. Baxter
J. W. Beams
H. T. Beans
H. Bethe
N. Bohr
H. A. Boorse
E. T. Booth
H. G. Bowen
G. E. Boyd
G. Breit
A. K. Brewer
L. J. Briggs
W. M. Brobeck
O. E. Buckley
V. Bush

G. H. Cady
S. T. Cantril
W. S. Carpenter, Jr.
J. Chadwick
T. H. Chilton
L. W. Chubb
W. M. Clark
J. D. Cockroft
K. Cohen
A. H. Compton
J. B. Conant
E. U. Condon
D. Cooksey
W. D. Coolidge
C. M. Cooper
C. D. Coryell
E. C. Creutz
R. H. Crist
L. M. Currie
F. Daniels
A. J. Dempster
R. L. Doan
R. W. Dodson
J. R. Dunning
C. H. Eckart
A. Einstein
L. P. Eisenhart
P. H. Emmett
T. F. Farrell
B. Feld
E. Fermi
R. P. Feynman
T. Finklestein
H. Fletcher
R. H. Fowler
J. Franck
E. B. Fred
O. R. Frisch
T. C. Gary
B. Gherardi
C. H. Greenewalt
A. von Grosse
L. R. Groves
R. Gunn
H. H. Halban
A. C. Helmholz
L. H. Hempelmann
A. L. Henne
G. Hertz
N. P. Heydenburg
N. Hilberry
J. C. Hoffman
T. R. Hogness
G. C. Hoover
F. A. Jenkins
I. B. Johns
W. C. Johnson
F. Joliot
I. Kaplan
J. W. Kennedy
K. H. Kingdon
G. B. Kistiakowsky
I. Langmuir
G. C. Laurence
C. C. Lauritsen
E. O. Lawrence
M. C. Leverett
W. K. Lewis
W. F. Libby
E. Mack, Jr.
C. J. Mackenzie
H. R. MacKenzie
J. H. Manley
F. T. Matthias
E. T. McBee
E. McMillan
L. Meitner
J. B. Miles
W. T. Miller
E. W. Mills
A. C. G. Mitchell
J. S. Mitchell
F. L. Mohler
T. W. Moore
R. G. Moses
R. S. Mulliken
E. V. Murphree
G. M. Murphy

R. E. Newell
K. D. Nichols
A. O. Nier
F. C. Nix
E. O. Novis
M. L. E. Oliphant
F. Oppenheimer
J. R. Oppenheimer
F. A. Paneth
W. E. Parkins, Jr.
W. S. Parsons
H. C. Paxton
G. B. Pegram
R. Peierls
I. Perlman
B. Peters
G. Placzek
C. B. Pierce
W. R. Purnell
W. B. Reynolds
J. R. Richardson
R. B. Roberts
C. J. Rodden
F. D. Roosevelt
Ruhoff
E. Rutherford
A. Sachs
B. W. Sargent
G. T. Seaborg
E. Segré
R. Serber
F. Simon
F. G. Slack
C. B. Slade
J. C. Slater
J. Slepian
D. H. Sloan
C. S. Smith
L. P. Smith
H. D. Smyth
T. A. Solberg
B. Somervell
F. H. Spedding
E. W. R. Steacie
J. C. Stearns
H. L. Stimson
R. S. Stone
W. D. Styer
L. Szilard
H. S. Taylor
E. Teller
E. W. Thiele
G. P. Thomson
R. L. Thornton
R. C. Tolman
M. A. Tuve
H. C. Urey
A. A. Vernon
H. C. Vernon
J. H. van Vleck
G. M. Volkoff
A. C. Wahl
M. H. Wahl
H. A. Wallace
E. T. S. Walton
S. L. Warren
W. W. Watson
L. H. Weed
G. Weil
V. S. Weisskopf
E. G. Wever
J. A. Wheeler
M. D. Whitaker
R. Williams
E. Wigner
H. A. Wilhelm
R. R. Wilson
V. C. Wilson
W. H. Zinn
Allis-Chalmers Co.
Bakelite Corp.
Bell Telephone Labs.
Canadian Radium & Uranium Co.
Carbon & Carbide Chemicals Corp.
Carnegie Institution of Washington

Columbia University
Consolidated Mining & Smelting Co.
Cornell University
E. I. du Pont de Nemours & Co.
General Electric Co.
Harshaw Chemical Co.
Harvard University
Hooker Electrochemical Co.
Houdaille-Hershey Corp.
Iowa State College
Johns Hopkins University
J. A. Jones Construction Co., Inc.
Kellex Corp.
M. W. Kellogg Co.
Mallinckrodt Chemical Co.
Mass. Institute of Technology
Metal Hydrides Co.
National Bureau of Standards
National Carbon Co.
Ohio State University
Princeton University
Purdue University
Rice Institute
Rockefeller Foundation
Speer Carbon Co.
Standard Oil Development Co.
Stanford University
Stone & Webster Engineering Corp.
Tennessee Eastman Co.
Union Carbide & Carbon Corp.
University of Birmingham
University of California
University of Chicago
University of Illinois
University of Indiana
University of Minnesota
University of Virginia
University of Wisconsin
U. S. Army
U. S. Graphite Co.
U. S. Navy
Vanderbilt University
Westinghouse Electric & Mfg. Co.
Yale University

Appendix II: Canadian Development

Since the latter part of 1942 a large group of Canadian scientists has been working on the atomic energy problem in close connection with the work under way in the United States. At a huge laboratory in Montreal, a staff of three hundred chemists and physicists devoted months of experimentation and research effort to developing an alternative method for manufacturing plutonium. This project was supervised by C. J. Mackenzie, President of the National Research Council of Canada; the actual direc-

tion of the Montreal Atomic Energy Laboratory was in the hands of J. D. Cockroft, who performed the first transmutation with particles accelerated by high voltage, and of E. W. R. Steacie of the National Research Council.

As a result of all this work, a pilot plant has been erected at Chalk River (Petawawa), Ontario, which will be devoted to experimental work on the adaptation of atomic energy to industrial purposes. The distinctive feature of this Canadian development is the fact that it involves the use of heavy water rather than graphite as a moderator in the formation of plutonium. As previously pointed out, this method had been tried experimentally at Chicago, but was not utilized in the United States production program. The plant at Chalk River requires the same heavy concrete shielding and remote control operation that are found at Oak Ridge and Hanford.

Throughout the course of the joint British-United States-Canadian program, leading Canadian scientists cooperated to the fullest extent with workers in the United States. Two facts contribute to making Canada an excellent location for atomic energy projects: the first is the accessibility of uranium ore, and the second is the vast areas of comparatively uninhabited territory where there is likely to be little danger to the general public from radiation and where it is a simple matter to maintain any required degree of secrecy.

Appendix III: Sharing the Secret

SINCE THE FIRST printing of this book, numerous highly qualified scientists have taken opposite sides on the question of sharing with other nations the "know how" of manufacturing the atomic bomb. It was stated on page 175 that whatever technical information is not generally known should be made available to those nations which were allied with us in the late war, and that the entire matter of atomic power should be controlled by some authority to be established under the United Nations Organization. The authors are still of this opinion. To give an idea, however, of the variation of viewpoints on this crucially important matter, they wish to quote without further comment two recent statements.

Writing in the *Atlantic Monthly* of November 1945, Albert Einstein stated: "I do not believe that the secret of the bomb should be given to the United Nations Organization. I do not believe that it should be given to the Soviet Union. . . . The secret of the bomb should be committed to a world government, and the United States should immediately announce its readiness to give it to a world government."

David Dietz, Science Editor of the Scripps-Howard newspapers, wrote as follows on November 29th, 1945: "I think that now the reader of this column knows that it is the considered opinion of the leading scientists of America that the secret cannot be kept and that in trying to keep the thing a secret we shall run the danger of precipitating an atomic bomb race which can only end in the destruction of civilization."

Index

[Numbers refer to sections, not to pages]

A

B

C

[*Numbers refer to sections, not to pages*]

[*Numbers refer to sections, not to pages*]

[*Numbers refer to sections, not to pages*]

[*Numbers refer to sections, not to pages*]

[*Numbers refer to sections, not to pages*]

[*Numbers refer to sections, not to pages*]